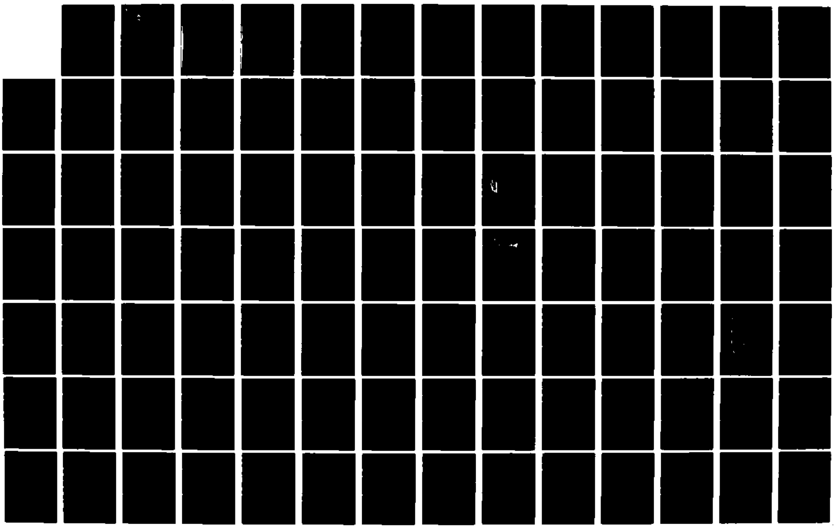
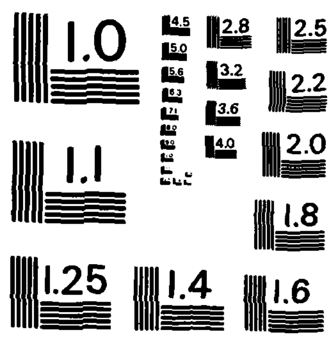
AD-A121 647 ABSTRACTS: 1982 AFOSR CONTRACTORS MEETING ON AIR BRETTHING COMBUSTION DYN..(U) UNIVERSITY OF SOUTHERN CALIFORNIA LOS ANGELES DEPT OF MECHANI.. 1/3

UNCLASSIFIED M GERSTEIN ET AL. NOV 82 AFOSR-TR-82-0841 F/G 21/1 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AFOSR-TR- 82-0841

(10)

UNIVERSITY OF
SOUTHERN CALIFORNIA
SCHOOL OF ENGINEERING

USC

AD A121647

DTIC
ELECTE
NOV 22 1982
S
A

Approved for public release;
distribution unlimited.

DTIC FILE COPY

MECHANICAL ENGINEERING DEPARTMENT

82 11 22 026

ABSTRACTS

1982 AFOSR CONTRACTORS MEETING

ON

AIR BREATHING COMBUSTION DYNAMICS RESEARCH

DTIC
ELECTE
NOV 2 2 1982
A

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFSC)
NOTICE OF TRANSMITTAL TO DTIC
This technical report has been reviewed and is
approved for public release IAW AFR 190-12.
Distribution is unlimited.
MATTHEW J. [illegible]
Chief, Technical Information Division

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFOSR-TR- 82-0841
2. GOVT ACCESSION NO.:
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): 1982 AFOSR CONTRACTORS MEETING ON AIR BREATHING COMBUSTION DYNAMICS RESEARCH
5. TYPE OF REPORT & PERIOD COVERED: INTERIM
6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s):
   Dr. M. Gerstein
   Dr. R. Choudhury
8. CONTRACT OR GRANT NUMBER(s): AFOSR-82-0222
9. PERFORMING ORGANIZATION NAME AND ADDRESS:
   UNIVERSITY OF SOUTHERN CALIFORNIA
   LOS ANGELES, CA 90007
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:
   2308 A2
   61102F
11. CONTROLLING OFFICE NAME AND ADDRESS:
   AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA
   BOLLING AFB, DC 20332
12. REPORT DATE: November 1982
13. NUMBER OF PAGES: 197
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
15. SECURITY CLASS. (of this report): UNCLASSIFIED
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:
16. DISTRIBUTION STATEMENT (of this Report):
   Approved for public release; distribution unlimited.
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):
18. SUPPLEMENTARY NOTES:
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

RAM JETS	REACTING FLOW DIAGNOSTICS	COMBUSTION INSTABILITY
GAS TURBINES	IGNITION	PARTICLE DYNAMICS
COMBUSTION MODELING	HOMOGENEOUS COMBUSTION	PREMIXING/PREVAPORIZING COMBUSTIO
FUEL-AIR EXPLOSIONS	HETEROGENEOUS COMBUSTION	CATALYTIC COMBUSTION
EXPLOSION	FLAME EXTINGUISHMENT	RAPID EXPANSION BURNING

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The report consists of a collection of expanded abstracts of the numerous research progress reports given by AFOSR supported contractors on the Air Force basic research program on Energy Conversion Related to Air-Breathing Propulsion and Explosions and of invited papers from other governmental agencies and contractors. These papers presented over a four-day period composed the 1982 contractors meeting on Air-Breathing Combustion Dynamics Research. The principal investigators and their organizational association are also identified.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

AGENDA

1982 AFOSR CONTRACTORS MEETING

on

AIRBREATHING COMBUSTION DYNAMICS RESEARCH

November 1-4, 1982

Surfside Holiday Inn
Clearwater Beach, Florida

8:00-9:30 p.m. SUNDAY, October 31, 1982 (Early registration--Surfside Holiday Inn)

Monday A.M. Session

8:00 a.m. Official Registration -- Surfside Holiday Inn

8:30 Welcome -- AFOSR Program Manager and Meeting Coordinator

B.T. Wolfson
Air Force Office of Scientific Research (AFOSR)

8:35 Morning Chairman

B.T. Wolfson

8:45 Future Directions In AFOSR Energy Research

M. Salkind

Director of Aerospace Sciences Directorate
US Air Force Office of Scientific Research (AFOSR)

9:10 Army Supported Research and Development Trends and Research Needs in Airbreathing Combustion, Kinetics and Explosions

D. Mann
US Army Research Office (ARO)

9:35 Navy Supported Research and Needs in Airbreathing Combustion, Kinetics and Explosions

A. Wood
US Office of Naval Research (ONR)

10:00 NASA In-House and Supported Research, Development Trends and Research Needs in Airbreathing Combustion

E.J. Mularz
NASA-Lewis Research Center

10:25 BREAK

10:40 a.m. NASA In-house and Supported Research - Development Trends and Research Needs in Gas Turbine Engine Combustion

Robert Jones
NASA, Aerothermodynamics and Fuels Division

11:05 DOE Supported Research and Needs in Basic Energy Sciences Associated with Airbreathing Combustion Dynamics, Kinetics and Explosions

W. Adams
Department of Energy/Office of Basic Energy Sciences

11:30 NASA Turbine Engine Hot Section Technology Program (HOST)

D.J. Gauntner
NASA-Lewis Research Center

11:55 NSF Supported Research and Needs in Basic Energy Sciences Associated with Airbreathing Combustion, Kinetics and Explosions

R. Rostenbach
National Science Foundation

12:20 p.m. LUNCH

Monday P.M. Session

1:45 p.m. Afternoon Chairman

D. Mann
US Army Research Office (ARO)

1:50 APL In-House Supported Research, Development Trends and Needs in Ramjet Combustion

R. Craig & D. Stull
Aero Propulsion Laboratory
AF Wright Aeronautical Laboratories (AFWAL)

2:15 APL In-House and Supported Research, Development Needs in Turbo Propulsion Combustion Technology

J. Petty
Aero Propulsion Laboratory
Wright Aeronautical Laboratories (AFWAL)

2:40 Injection, Atomization, Ignition and Combustion of Liquid and Multiphase Fuels in High-Speed Air Streams

J. Schetz
VPI and State University

3:05 p.m. Fundamental Modeling of 3-Dimensional Multiphase Reacting Flow Systems

J. Swithenbank
Sheffield University, England

3:30 BREAK

3:45 Turbulent Combustion Modeling and Experiments

K.N.C. Bray
University of Southampton, England

4:10 Modeling and Prediction of Reacting Turbulent Flow Characteristics

W.M. Pitts
National Bureau of Standards - Gaithersburg, MD

4:35 Mixing, Ignition and Combustion in Flowing Reacting Fuel-Air Mixtures

R.B. Edelman & P.T. Harsha
Sciences Applications Inc.

5:00 ADJOURN

DTIC
COPY
INSPECTED
2

Accession For
A

Tuesday A.M. Session

8:00 a.m. Morning Chairman

J. Petty
Aero Propulsion Laboratory
AF Wright Aeronautical Laboratories (AFWAL)

8:05 Fundamental Studies of Chemical Reactions in High Speed Turbulent Flows

H. Liepmann, Rosko and Dimotakis
California Institute of Technology

8:30 Coherent Structures in Turbulent Flames

N. Chigier
Carnegie-Mellon University

8:55 Application of Multi-Dimensional Modeling Techniques to the Design and Development of Gas Turbine Combustors

H. Mongia
Garrett Institute Engine Company

9:20 Fundamental Combustion Studies with Conventional and Alternate Fuel Sprays Under High Air Temperature and Pressure Conditions

J. Peters, H. Krier and K. Kim
University of Illinois

9:45 Ionic Mechanisms of Carbon Formation in Flames

H.F. Calcote
Aerochem Research Laboratories Inc.

10:10 BREAK

10:25 Turbulent Mixing and Combustion of Multi Phase Reacting Flows in Ramjet and Ducted Rocket Environments

K. Schadow
Naval Weapons Center

10:50 Fundamental Studies in High Energy - High Density Fuel Ignition and Combustion in Ramjet and Ducted Rocket Environenments

M. King
Atlantic Research Corporation

11:15 a.m.	Baron Slury Combustion in Turbulent Reacting Flows F.A. Williams Princeton University
11:40	Combustion Studies of High Energy - High Density Fuels and Predictions of Spray Combustion Interactions G. M. Faeth Pennsylvania State University
12:05 p.m.	LUNCH

Tuesday P.M. Session

1:45 p.m.	Afternoon Chairman D.F. Stull Aero Propulsion Laboratory AF Wright Aeronautical Laboratories (AFWAL)
1:50	Research and Supersonic and Dual Mode Combustion at NASA-Langley Research Center G.B. Northam NASA-Langely Research Center
2:15	Combustor Inlet Interactions and Modeling of Dual - Combustion Hypersonic Ramjet Engine P. Walthrup Applied Physics Lab/Johns Hopkins University
2:40	NAVY Research Development Trends and Research Needs in the Area of Ramjet Combustion Instability W. Clark Naval Weapons Center
3:05	BREAK
3:20	Mechanisms of Exciting Pressure Oscillations in Ramjet Engine Environments F. Culick California Institute of Technology
3:45	Basic Instability Mechanisms in Chemically Reacting Turbulent Flows T.Y. Toong Massachusetts Institute of Technology

4:10 p.m.	Modeling of Augmentor Combustion Instability R.C. Ernst Pratt-Whitney Government Products Division
4:35	ADJOURN
7:00	SOCIAL -- Surfside Holiday Inn
8:00	BANQUET -- Surfside Holiday Inn

Wednesday A.M. Session

8:30 a.m. Morning Chairman

Maj. T. Slankas
AF Engineering Services (Enter/Tyndall AFB, Florida)

8:35 Status of the Utilization of New and Alternative Fuels in Air-breathing Turbine and Ramjet Engines

C. Martel, C. Delaney, J. McCoy & Capt. Potter
Aero Propulsion Laboratory
AF Wright Aeronautical Laboratories (AFWAL)

9:00 Problems in the Compatability of Future Fuels with Current Air-breathing Combustion Systems

C.A. Moses
Southwest Research Institute
and
A.M. Mellor
Drexel University

9:25 Chemical Kinetic Issues Associated with Combustion Generated Emissions from Conventional and Alternative Fuels in Air-breathing Engines.

A. Levy
Battelle Columbus Research Labs

9:50 AFESC Supported Research and Needs Associated with Gas Turbine. Turbine Engine Eission and Other Combustion Related Problem

Maj. T. Slankas & Capt. D. Berlinrut
AF Engineering Services Center/Tyndall AFB, Florida

10:15 BREAK

10:30 Fuel Additive Effects on Sooting Flames

P.A. Bonczyk & A.F. Eckbreth
United Technology Research Center

10:55 Pyrolysis, Oxidation and Reaction Kinetics of Hydrocarbons and Alternative Fuels

I. Glassman & F. Dryer
Princeton University

11:20 a.m. Mechanisms of Exhaust Pollutant and Plume Formation in Continuous Combustion

G. S. Samuelsen
University of California - Irvine

11:45 The Behaviour of Detonation Waves in Single Phase

D.H. Edwards
Department of Physics, University College of Wales, Aberystwyth, Wales, United Kingdom

12:10 p.m. LUNCH

Wednesday P.M. Session

1:45 p.m. Afternoon Chairman

C. Martel
Aero Propulsion Laboratory
AF Wright Aeronautical Laboratories (AFWAL)

1:50 Measurement of Turbulence in Combustion Systems by Raleigh Scattering

L. Talbot and F. Robbins
University of California - Berkeley

2:15 Interfacial Chemical Reactions in Flow Systems

D.F. Rosner
Yale University

2:40 Airbreathing Propulsion Research at Technion

A. Gany
Technion University - Israel

3:05 BREAK

3:20 Transient Combustion Dynamics, Fuel Droplet Decomposition and breakup

M.Gerstein & P. Roy Choudhury
University of Southern California

3:45 A Proposed Investigation of Spray Vaporization and Combustion In A Recirculation Flow

T.R. Troutt, J.N. Chung and S. Wojcicki
Washington State University

4:10 Executive Session (AFOSR CONTRACT/GRANTS ONLY)

4:40 ADJOURN

Thursday A.M. Session

8:30 a.m. Morning Chairman

W.M. Roquemore
Aero Propulsion Laboratory
AF Wright Aeronautical Laboratories (AFWAL)

8:35 Research at LLL on Advanced Diagnostic Techniques and Air-breathing Combustion Dynamic Related Phenomena

D.L. Hartley
Sandia-Lawrence Livermore Laboratories

9:00 Studies of Combustion Processes in APL Combustion Research Facility

R.P. Bradley & W.M. Roquemore
Aero Propulsion Laboratory
AF Wright Aeronautical Laboratories (AFWAL)

9:25 Rapid Scanning of Temperature and Velocity Profites in Chemically Reacting Flow Systems

H. Sommer
Carnegie-Mellon University

9:50 High Temperature Catalytic Combustion

F. Bracco & Royce
Princeton University

10:15 BREAK

10:30 Radiation Enhanced Ignition, Combustion and Flame Stabilization

I. Crane
Exxon Research and Engineering Company

10:55 Effect of Intense Laser Radiation on Promoting Ignition and Enhancing Combustion of Fuels

W. Braun & M.D. Scheer
National Bureau of Standards - Gaithersburg, MD

11:20 Ignition of Fuel Sprays by Hot Surfaces and Stabilization of External and Void Space Aircraft Fires

A.H. Lefebvre, J.C. Skifstad & S.N.B. Murthy
Purdue University

11:45 a.m. Ignition of Fuels by Incendiary Metal Particles

W.A. Sirignano
Carnegie-Mellon University

12:10 p.m. LUNCH

Thursday P.M. Session

1:45 p.m. Afternoon Chairman

B.T. Wolfson
Air Force Office of Scientific Research (AFOSR)

1:50 Ignition of Fuels Under High Intensity Laser Radiation

T. Kashiwagi
National Bureau of Standards, Gaithersburg, MD

2:15 Mechanisms of Direct Shockless Initiation of Unconfined Fuel - Air Detonations

J. Lee, R. Knystautas, I. Moen & C. Guirao
McGill University - Canada

2:40 Ignition, Acceleration, Stability and Limits of Detonation

H. Wagner & W. Jost
University of Wales - England

3:05 BREAK

3:20 Detonation Characteristics of Some Dusts and Liquid-Dust Suspensions

J.A. Nicholls, C.W. Kauffman, S. Sichel & P. Lee
University of Michigan

3:45 Ignition Combustion, Detonation and Quenching of Flames and Detonations in Reactive Mixtures and Related Phenomena

R. Edse
Ohio State University

4:10 ADJOURN

FUTURE DIRECTIONS IN AFOSR ENERGY RESEARCH

M. Salkind
US AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFOSR)

ABSTRACT NOT AVAILABLE

Army Supported Research and Development
Trends and Research Needs in the Areas of
Air Breathing Combustion, Kinetics and Explosions

Dr. David M. Mann
Army Research Office

Engine research focuses on obtaining the understanding necessary for the development of more efficient engines which are capable of operating on a broad range of fuels. Due to their dominance in Army systems, the program is directed at diesel and turbine engines. In both engine types, increased efficiency will result from higher temperature, higher pressure operation with the combustion process tailored to optimize energy release. Accordingly basic studies are being conducted on fuel sprays, flame propagation and fuel/flame surface interactions. The development of advanced diagnostic instrumentation is necessary to probe the particularly hostile combustion regions in these engines and provide the data needed for an understanding of the internal combustion dynamics. The internal fluid dynamics of small gas turbines is being studied to define approaches to more compact, higher efficiency engines. Accordingly, research investigations in this area are concentrated on strongly three-dimensional flows in ducts, secondary flow patterns, compressor-diffuser interfaces, heat transfer mechanisms, variable geometry effects and erosion mechanisms in dusty gas environments. Operation on broad spectrum or alternate fuels requires understanding of the changes in fuel handling, engine design and operation necessary to obtain maximum efficiency and engine life. Therefore studies of the physical properties and combustion behavior of these fuels are being done to determine their potential effect on engines. Concepts for advanced engine control are being investigated as techniques to provide increased fuel tolerance and response to engine load demands.

Research on power generation is focused on fuel cell and MHD technology. Increased efficiency and durability from fuel cells require improved catalysts which are tolerant of fuel impurities. Studies are concentrating on catalytic reaction mechanisms and reversible electrode processes for regenerative catalysts. Pulsed plasma MHD (magnetohydrodynamic) generators have a potential for high peak power but need further research to get systems of acceptable efficiency.

Gun propulsion research is focused on propellant properties, particularly shock sensitivity, propellant combustion and the combination of combustion, fluid mechanics and mechanics known as "interior ballistics," combustion related barrel erosion phenomena and muzzle flash resulting from atomospheric burning of muzzle exhaust gases. Analytical and experimental programs are studying the details of propellant combustion flames, multiphase reacting flow and heat and mass transfer in gun combustion environments. The goal is to provide the understanding necessary for the development of more effective gun systems with reduced empirical testing.

Optimization of explosive weapon effectiveness requires an understanding of detonation processes in conventional and unconventional explosives. Studies are being conducted on the dynamics of detonation propagation in solid and fuel-air explosives.

NAVY SUPPORTED RESEARCH AND NEEDS IN AIRBREATHING COMBUSTION, KINETICS AND EXPLOSIONS

A. Wood

US Office of Naval Research (ONR)

ABSTRACT NOT AVAILABLE

NASA IN-HOUSE AND SUPPORTED RESEARCH - DEVELOPMENT TRENDS AND RESEARCH NEEDS IN COMBUSTION FUNDAMENTALS

EDWARD J. MULARZ

Head, Combustion Fundamentals Section
NASA Lewis Research Center and
Propulsion Laboratory, USARTL

The combustion research and technology programs that are conducted and managed by the NASA LeRC Combustion Branch cover a wide spectrum of activities, from fundamental studies of combustion phenomena to applied research efforts on gas turbine combustors. The focus of these programs is to provide the fundamental information, analytical models, and generic information to designers of future gas turbine engines.

Over the last few years increased emphasis has been placed on fundamental and generic research at LeRC with less systems development efforts. This is especially true in combustion research where the area of combustion fundamentals has grown significantly in order to better address the perceived long term technical needs of the aerospace industry. The main thrusts for this combustion fundamentals program are as follows:

<u>Analytical Models of Combustion Processes</u>
Analytically characterize the governing physical phenomena which occur during combustion and in the fluid dynamic processes associated with gas turbine combustors.

<u>Model Verification Experiments</u>
Provide benchmark quality data to assess the accuracy of analytical models and to identify model deficiencies.

<u>Fundamental Combustion Experiments</u>
Achieve a more complete and basic understanding of the fundamental aerodynamic and chemical processes occurring in chemically reacting flows.

<u>Advanced Numeric Techniques</u>
Improve computer codes in terms of efficiency, numerical accuracy, and display of results.

In each of these areas there are several research projects, including grant activities, contracts, and in-house projects. A review of these projects was recently held at LeRC, and a conference publication with project summaries will be published. This presentation will give an overview of the program with several projects highlighted as examples of the program.

NASA IN-HOUSE AND SUPPORTED RESEARCH - DEVELOPMENT TRENDS AND RESEARCH NEEDS IN GAS TURBINE ENGINE COMBUSTION

Robert Jones

The combustion research and technology programs that are conducted and managed by the Combustion Branch cover a wide spectrum of activities, from fundamental studies of combustion phenomena to applied research efforts on gas turbine combustors. The focus of these programs is to provide the fundamental information, analytical models and generic information to designers of future gas turbine engines.

These programs are conducted through a balanced effort comprised of university grants, industry contracts and in-house research. The selection of which mode to employ depends upon the nature of the work, skills and capabilities available, compatability with our long-term goal and the extent and availability of resources.

In the past year and a half, the nature of the Branch effort related to combustors and combustor components has undergone a marked change. Previous combustor efforts were characterized by extensive research into new combustor concepts to meet anticipated environmental regulation or to contend with changes to the fuel or the combustor environment. These efforts were usually funded to high dollar values as was necessitated by our desire for final evaluation in a gas turbine engine. The shift in emphasis to fundamental combustion research has had a impact on the combustor technology programs. The emphasis in combustor-technology now is in the area of generic research. These contracted programs tend to be typically of a smaller dollar value, for a shorter period of performance and generally are intended to determine the impact or effect of one component or parameter upon another or others. These studies provide a basis for the development and verification of analytical models of combustor performance.

The program plan that has been constructed in combustors and combustor components is heavily involved in generic research. All areas of combustor technology are under review to identify where information and understanding are needed to enhance modeling.

The emphasis in future gas turbine engine research is significantly effected by the needs of the industry. These needs are enhanced durability, performance at high pressure and temperature, fuel flexibility, low smoke and emission levels, increased design and development productivity and reduced initial cost. The programs that have been planned and are underway are responsive to these needs. The generic technology efforts in combustors and combustor components, when coupled with the fundamental combustion research programs will lead to the development, improvement and validation of functional models for combustors. With time and experience, the reliability and acceptance of such models will grow. The ultimate impact will be significantly shorter combustor design and development times as well as an inherently better and more comprehensive understanding of all the involved processes occurring within gas turbine combustors.

The oral presentation will discuss the present needs and trends in gas turbine combustor research and will outline many of the present activities that are underway and planned.

DOE SUPPORTED RESEARCH AND NEEDS IN BASIC ENERGY SCIENCES ASSOCIATED WITH AIR-BREATHING COMBUSTION DYNAMICS AND KINETICS

O. W. Adams

Office of Basic Energy Sciences (BES)
U.S. Department of Energy
Washington, D.C. 20545

The BES/USDOE combustion research program is made up largely of projects in the areas of combustion diagnostics, chemical kinetics, fluid dynamics, theory and applied mathematics. Some modeling is supported in connection with individual projects. The level of effort was about $10.5M in FY 1982. It covers projects in two divisions of BES, the Chemical Sciences Division and the Engineering, Mathematics and Geosciences Division. In addition, the Materials Sciences Division of BES supports two projects in combustion materials research.

A major component of the combustion program is centered at the Combustion Research Facility (CRF) at the Sandia National Laboratory-Livermore. That research will be described separately at this meeting. The main emphasis of the projects at CRF is on combustion diagnostics, both their development and application, but there is also a well rounded basic and applied combustion program, a large part of which is also supported by BES.

The chemical kinetics projects supported by BES range from those using the molecular beam technique to those using shock tubes and also includes a kinetic data evaluation project at the National Bureau of Standards. Most of the projects are concerned with the combustion of aliphatic hydrocarbons but attention is also given to reactions involving aromatic hydrocarbons. A current program emphasis is aimed at understanding the mechanism of soot formation. A strong theoretical combustion kinetics effort is also being maintained.

The BES effort in fluid dynamics is small but will grow. The emphasis is given primarily to fluid dynamics related to combustion modeling and accordingly includes experimental and theoretical aspects of turbulence, mixing and two phase flow.

NASA TURBINE ENGINE HOT SECTION TECHNOLOGY PROGRAM (HOST)

D.J. Gauntner

NASA-Lewis Research Center

ABSTRACT NOT AVAILABLE

NSF Supported Research and Needs in Basic Energy Sciences Associated with Airbreathing Combustion, Kinetics and Explosions

Royal E. Rostenbach
National Science Foundation

The Engineering Energetics Program* presently supports 27 basic research grants, 5 specialized research equipment grants, and 3 conference grants related to combustion. The research is conducted but not limited to the following areas: turbulent combustion; flame dynamics; coal combustion; jet ignition; internal combustion engines; diesel engines; detonation; and diagnostics. The research is done prmmarily at universities.

* Division of Chemical and Process Engineering, National Science Foundation, Washington, D. C. 20550

COMBUSTION GRANTS

TURBULENT COMBUSTION

University of California Berkeley	John W. Daily	Experimental Investigation of Turbulent Combustion Stabilized in a Free Shear Layer	$ 78,254 12 mos.
University of California Irvine	G. Scott Samuelsen John C. LaRue	Investigation of Turbulent, Backmixed, Gaseous Combustion	$154,357 24 mos.
Carnegie-Mellon University AeroChem Research Laboratories	William A. Sirignano Hartwell F. Calcote	Turbulent Chemically Reacting Axisymmetric Jets	$400,100 24 mos.
Columbia University New York City	Robert G. Bill, Jr.	Effects of Turbulence of Recirculation Vortex Shedding and Flame Stabilization Mechanisms	$ 63,342 12 mos.
Columbia University New York City	Rene Chevray	Gas Phase Reaction in a Turbulent Jet	$ 35,530 12 mos.
Cornell University	Stephen B. Pope	Monte Carlo Calculations of Turbulent Flames	$ 23,952 12 mos.
University of Illinois Chicago Circle	Kartik V. Dandekar	Design of a Combustor for Premixed Turbulent Flame Study	$ 47,495 24 mos.

COMBUSTION GRANTS

FLAME DYNAMICS

University of California Los Angeles	Owen I. Smith	Sulfur Catalyzed Radical Recombination in Flames	$ 66,848 12 mos.
University of Colorado Boulder	Melvyn C. Branch	Nitric Oxide Reduction by Ammonia Addition to Post Flame Gases	$ 52,669 18 mos.
Harvard University Factory Mutual Research Corp.	Howard W. Emmons John de Ris	Diffusion Flame Energy Transfers	$328,494 24 mos.
University of Illinois Urbana	John D. Buckmaster	Pulsations, Bifurcations, and Related Phenomena Important in Flame Stability	$ 31,998 12 mos.
University of Pennsylvania	Stuart W. Churchill	Modelling the Combustion of Premixed Gaseous Fuels in a Refractory Tube	$ 71,000 12 mos.
Princeton University	Forman A. Williams	Studies of Mechanisms by Which Dry Powders Aid in Extinguishment of Diffusion Flames for Condensed Fuels	$ 75,629 24 mos.
University of Washington	Philip C. Malte	Effect of Fuel-Sulfur on the Formation and Yield of Fuel-Oxides of Nitrogen in Combustion Systems	$ 90,000 30 mos.

COMBUSTION GRANTS

JET IGNITION

University of California Berkeley	Antoni K. Oppenheim	Study of Jet Ignition in Lean Gas Mixtures	$ 80,000 12 mos.
University of Connecticut	Eli K. Dabora	Plasma Jet Ignition of Lean Fuel-Air Mixtures	$ 69,043 12 mos.

INTERNAL COMBUSTION ENGINES

University of Santa Clara	Richard K. Pefley	Combustion of Alcohol and Biogas	$ 20,000 36 mos.
Princeton University	Frediano V. Bracco	Experimental Assessment of Two-Dimensional, Unsteady Models for Uniform Charges	$190,142 36 mos.

COMBUSTION GRANTS

COAL COMBUSTION

Coal Tech Corp.	Bert Zauderer	Sulfur Captute with Limestone Injection in Cyclone Combustion	$ 28,037 06 mos.
Energy and Environmental Research Corp.	John H. Pohl W. R. Seeker	Improved Coal Flame Detection	$ 29,999 06 mos.

IGNITION-POLYMERS

University of Texas Austin	Ronald D. Matthews	Experimental and Theoretical Investigation of Synthetic Polymer Ignition	$ 24,968 24 mos.

DETONATION

University of Michigan Ann Arbor	James A. Nicholls Martin Sichel C. William Kauffman	Detonation Combustion of Coal, Grain, and Other Dusts	$172,000 24 mos.

DIESEL ENGINES

Drexel University	Nicholas P. Cernansky	Chemistry and Physics of Oxygenate and Odor Formation in Diesel Engines	$ 71,000 12 mos.

COMBUSTION GRANTS

DIAGNOSTICS

Cornell University	Terrill A. Cool	Resonance Ionization Probe Techniques for Combustion Diagnostics	$ 38,000 09 mos.
SRI International	David R. Crossley	Laser Spectroscopy for Combustion	$182,906 24 mos.
Stanford University	Ronald K. Hansen Charles H. Kruger	Absorption and Fluorescence Techniques for Flow Reactors Studies	$ 80,000 12 mos.
Stanford University	Sidney A. Self	Diagnostic Techniques for Magnetohydrodynamics and Related Plasma Flows	$226,045 36 mos.

COMBUSTION GRANTS

RESEARCH EQUIPMENT

Drexel University	Richard S. Cohen Nicholas P. Cernansky	Laboratory Data System	$38,812 12 mos.
Drexel University	Nicholas P. Cernansky Richard S. Cohen	Specialty Detectors	$ 9,000 9 mos.
University of Illinois Chicago Circle	John H. Keifer	Laser System	$20,000 12 mos.
Kansas State University	Thomas W. Lester Joseph F. Merklin	Analytical Instrumentation	$23,200 12 mos.
University of Washington	Philip C. Malte Barbara B. Krieger Harold E. Hager	Tunable Dye Laser	$40,000 18 mos.

COMBUSTION GRANTS

CONFERENCES

Combustion Institute	Raymond Friedman	International Symposium-1982 Publication of Papers	$ 6,000 12 mos.
Combustion Institute	Raymond Friedman	International Symposium-1982 Travel by Individuals	$ 7,200 6 mos.
University of Washington	J. Ray Bowen	International Colloquium on Gasdynamics of Explosions and Reactive Systems-1981, Publication of the Proceedings	$10,500 12 mos.

AIR FORCE IN-HOUSE RESEARCH ON RAMJET COMBUSTORS

R. R. Craig, R. S. Boray, P. L. Buckley, D. L. Davis, K. G. Schwartzkopf and F. D. Stull

Air Force Wright Aeronautical Laboratories
Aero Propulsion Laboratory
Ramjet Engine Division
Ramjet Technology Branch
Wright-Patterson AFB, Ohio 45433

Dump combustors (co-axial or side entry) have become the basis for modern volume limited ramjet missile designs. Since the combustor must generally contain the rocket boost propellant in an integral rocket/ramjet design, use of conventional can combustors is not permitted. Flame stabilization depends largely on the recirculation zone formed by the sudden area change at the inlet duct, combustor junction. Additionally, if required, flameholders may be placed in the inlet duct resulting in a substantial, additional pressure loss. Although many such combustors have been successfully fabricated and tested over the past several years, the specific nature of these prior designs have precluded obtaining a sound technical data base or detailed flowfield data necessary for combustor modeling efforts. Additionally, the dearth of operational ramjet systems has prevented any significant IR&D effort involving the ramjet industry, and lack of air facility capabilities at the university level has limited university involvement in ramjet experimental research. The objective of the in-house research programs being conducted by the Ramjet Engine Division of the Aero Propulsion Laboratory is to provide such a data base for the development of compact ramjet combustors having wide ignition limits, high combustion efficiencies and low total pressure losses over a wide range of flight conditions, and to provide detailed flowfield data for validating combustor modeling efforts. Although the modeling approaches do predict details of the flowfield, their ultimate utility will be to predict overall performance and pressure losses, and these are the two quantities that our research has concentrated on accurately determining for various ramjet combustor configurations.

Our past research has demonstrated the practicality of using swirl in ramjet combustors with a L_c/D of 1.5 in small scale combustors. This work has been extended to 12" diameter combustors with a L_c/D of 1.0. Measurements have been confined to overall performance due to lack of means for making detailed measurements in highly swirling flows. A five-hole probe has been fabricated but still requires calibration. Laser Doppler Velocimeter (LDV) flowfield measurements will be made once our two-color backscatter system becomes operational. Predictions of mixing in the swirl combustor have been made using a modified version of D. G. Lilley's "STARPIC" code. Modifications to the code included sloping entrance and exit walls, compressibility, a simple combustion model and species equation solutions. These modifications were made by Dr. Warren H. Harch, a visiting scientist from Aeronautical Research Laboratories, Australia. Although the k-ε turbulence model has very serious limitations in predicting swirling flows, it did indicate that mixing of the fuel-air with a forced vortex swirl profile would be inferior to that of a free vortex. Combustion results with these two profiles can be interpreted as confirming this prediction.

Combustion performance parametrics have been conducted on a dual inlet, side-dump combustor. Detailed probing and surface flow patterns will begin shortly with completion of the checkout of the cold flow facility data acquisition. Data will be obtained from five-hole probe measurements and mixing studies with an on-line quadrapole mass spectrometer system. Water tunnel flow patterns and residence time measurements are being documented for the same configurations. Flow pattern predictions are being made by Dr. S. P. Vanka, a visiting scientist from Argonne National Laboratories, using a 3-D Navier-Stokes code, "RAM3D," written while with us this summer. The turbulence model has the k-ε model limitations, and detailed flowfield data is currently unavailable for detailed comparisons.

Combustion instability studies have continued and have been expanded to include the duel-inlet side entry combustor. The low frequency instabilities are well correlated by Toong and Keklak's "Entropy Wave Model." However, prediction of when the instabilities occur is not currently in the model. The model has also been applied to predict attenuation of the instabilities, but experimental verification of the predictions has not yet been accomplished.

Two-component LDV measurements continue to be delayed by lengthy delays in fabrication of interfacing to the MODACS computer and by debugging of the data acquisition program. Backscatter measurements have permitted profiling of a cold-flow dump combustor model much nearer to the wall and have reaffirmed the magnitude of velocity biasing error in highly turbulent flows. Comparisons of this data with k-ε model predictions have been made by Dr. E. F. Brown from VPI while at the Aero Propulsion Laboratory under the AFOSR Summer Faculty Program. In general, the agreement was disappointing and points up the need for improved turbulence models.

Aero Propulsion Laboratory Research and Development Needs In Turbopropulsion Combustion Technology

Dr James S. Petty
Air Force Wright Aeronautical Laboratories
Wright-Patterson AFB, Ohio

In the Fall of 1978 a survey of the U. S. aircraft engine manufacturers was conducted by a joint Air Force-Army-Navy turbopropulsion combustion assessment team. From this survey, a technology assessment was prepared ("Turbopropulsion Combustion Technology Assessment", AFAPL-TR-79-2115, available from DTIC) which included the state-of-the-art, advanced technology trends, technology needs and a five-year plan.

An additional document was prepared detailing turbopropulsion research needs, based on the assessment ("Turbopropulsion Combustion Research Needs" by Mellor, Leonard and Henderson, ASME Paper 80-GT-164). Research needs were identified for main burners, afterburners, general turbopropulsion combustion modeling and alternative fuels. In brief summary, some of the research needs of interest in main burners include measurements to isolate the radiative and convective components of heat transfer to the combustor liner, improved understanding of and new concepts for the combustor inlet diffuser, improved understanding of the combustor-diffuser aerodynamic interaction and of the aerodynamics of the penetration jets within the combustor, and studies of the interaction between fuel spray quality and placement and the primary zone aerodynamics. Some appropriate areas for research on afterburners are improved mixing and flameholding techniques, and fuel autoignition, piloting, pyrolysis and injection techniques. Improved understanding of the basic phenomena involved in the onset of combustion instability are also required. In combustion modeling, validation of combustion models, including turbulence, fuel sprays and reaction kinetics is needed. The near-term research in modeling should be limited to non-reacting flows in the areas of diffuser aerodynamics, combustor diffuser interaction, penetration jet aerodynamics and cold flow simulations of the primary zone. Significant improvements are needed in the development of more efficient, less expensive and more "user friendly" combustor codes. Finally, measurements are needed for the validation of the various models. Fundamental research is required on the effects of fuel properties, such as aromatic and hydrogen content, viscosity and votalility, on ignitability, smoke and flame radiation in combustor environments.

A review of the technology assessment indicates that the conclusions reached, and the needs identified, remain valid. The programs being pursued by the Aero Propulsion Laboratory in turbopropulsion combustion still follow the general recommendations of the assessment.

INJECTION, ATOMIZATION, IGNITION AND COMBUSTION OF LIQUID AND MULTIPHASE FUELS IN HIGH-SPEED AIR STREAMS

Joseph A. Schetz

Aerospace and Ocean Engineering Department

Virginia Polytechnic Institute and State University

Transverse injection of liquid and/or liquid-slurry jets into high speed airstreams finds application in several propulsion-related systems. For supersonic flows, these include thrust vector control and external burning for projectiles as well as scramjet engines and for subsonic airstreams, "dump" combustors and afterburners, in addition to ramjets. All include physical processes associated with gross penetration, jet breakup and atomization, and some chemical processes. (See Fig. 1). Current work at Virginia Tech concentrates mainly on two aspects of the complex physical processes - breakup and atomization of slurry jets at high particle loadings and simulation of high vaporization rates along the plume spray as found with fuel injection into hot combustor flows by newly developed cold-flow testing techniques.

The experiments are conducted primarily in the Virginia Tech 23 cm. x 23 cm. Transonic/Supersonic Wind Tunnel at $0.4 \leq M \leq 4.0$ with $T_o = 300$ °K and $1.5 \leq P_o \leq 4.0$ atm. The instrumentation used is mainly optical involving high-speed motion pictures (up to 45,000 pic/sec.), short-duration photomicrographs (10^{-8} sec.), a rotating mirror camera to obtain two to four frames at a framing rate of 10^5 pic/sec. a laser for diffractively scattered light droplet size measurements and Charge Coupled Devices (CCD). The experiments are complemented by numerical solutions of various parts of the general problem.

One task in our overall research plan was brought to at least temporary completion this year. The studies of physical property effects were finished by including a very low surface tension injectant, Fluorinert, to extend the range of that important variable. Penetration and droplet sizes were measured.

Coordinated experimental and numerical studies of slurry jet breakup were pursued to the point where direct comparisons were possible for the case of injection into a medium at rest. Good agreement was obtained.

A new simulation scheme was developed for studying the effects of rapid vaporization in the spray plume by cold-flow testing. A representative ramjet combustor situation was simulated by chilled Freon-12 injection. Decreases in penetration and droplet size were documented. (See Fig. 2).

INJECTION, ATOMIZATION, IGNITION AND COMBUSTION OF LIQUID AND SLURRY FUELS IN HIGH SPEED AIR STREAMS

Virginia Polytechnic Institute and State University   Dr. J. A. SCHETZ, P. I.

Problem Description:
- Unsteady
- Three-dimensional
- Turbulent
- Two Phases (three with slurries)
- Mixed Subsonic/Supersonic
- Heat Release

Delineate Dominant Processes and Effects

Understand and Predict Basic Mechanisms

Provide Basic Data

<u>Experiments under Representative Conditions</u>

Supersonic/Transonic Tunnel
Variables Investigated
- Mach no., injectant rate
- Injection port size and shape
- Injectant viscosity and surface tension
- Slurry loading and part. size
- Vaporization along plume

Optical Techniques
- Nanosecond spark photos
- Rotating mirror camera for sequences of photos
- Diffractive scattering of laser light for drop size
- Absorption of laser light for phase separation
- Infrared thermography for heat release detection

<u>Analysis of Idealized Aspects of the Complete Problem</u>

Compare ⟷ to Refine Analyses

Marker and Cell method for numerical solution of axisymmetric Navier-Stokes equations with free surfaces

Compare surface wave growth and jet break-up with and without particles

Add effects of rapid vaporization along the jet

<u>Detailed, Basic Experiments of Idealized Aspects of the Complete Problem</u>

Liquid and Slurry jets with coaxial air flow

Same cases with conditions for high mass transfer rates

Observations
- Surface wave growth rates
- Wave size, shape
- Jet breakup
- Phase separation
- Droplet sizes
- "Satellite" drop formation

INJECTION, ATOMIZATION, IGNITION AND COMBUSTION OF LIQUID AND SLURRY FUELS IN HIGH SPEED AIR STREAMS

Virginia Polytechnic Institute and State University

Dr. J. A. SCHETZ, P. I.

Relevance to Air Force Needs

Applications:

- Fuel injection for ramjets/scramjets
- Fuel injection in turbojet augmentors
- Thrust vector control
- Missile control by jet injection
- Dumping of turbine blade coolant
- Slurries for high vol. heat release

Requirements:

- Fundamental understanding of processes and effects
- Data correlations
- Design analyses

One Primary Accomplishment in 1982

The Problem:

- Effects of rapid evaporation of liquid fuel in the spray plume due to injection into hot air stream in a combustor

The Approach:

- Developed a simulation scheme that permits testing under controlled, laboratory-environment conditions with cold air flow in a wind tunnel

The Solution:

- Perform rational, physical derivation leading to two similarity parameters

$$\sigma(T) \equiv \frac{P_{vap} - P_\infty}{\frac{1}{2}\rho V_\infty^2}$$

$$T^* \equiv \frac{T_{o,\infty} - T_j}{T_{o,\infty}}$$

that must be matched for simulation

Results:

- Simulate $M_\infty = 2.4$, h = 60,000 ft. ramjet with kerosene fuel and $M_{comb} = 0.44$ with chilled Freon-12 in a cold flow tunnel
- Penetration reduced slightly and droplet sizes reduced about 50% compared to tests neglecting vaporization along plume

Fundamental Study of Three Dimensional

Two Phase Flow in Combustion Systems

Joshua Swithenbank
Principal Investigator

Department of Chemical Engineering and Fuel Technology,
University of Sheffield,
Sheffield, England.

The long term objective of this research is to provide a rational, reliable and comprehensive design method for the various combustion systems (eg. gas turbine, ramjet, ducted rocket) of interest to the USAF. This goal would result in quicker and cheaper development of more versatile and innovative systems incorporating greater efficiency and operating limits, as well as providing insight into problem areas which are already to be found in existing technology.

The approach has been to develop and extend previous finite difference computer algorithms to the required level for application to 3-dimensional two phase hot flows Some of the results from this ambitious task have already been reported and have included droplet trajectory paths, fuel evaporation patterns and temperature profiles for a gas turbine can. Along side of this area of application to combustion systems have been the important areas of algorithm development and experimental verification. The algorithm development side of the work has been of particular importance due to the realisation that traditional turbulence representations seriously misrepresent the flow fields when large swirl is present. These flows are of increasing importance in high intensity combustors and as a preparation to modelling these correctly, fundamental work has proceeded with the development of a new algebraic stress model. This has been tested for a number of swirling flow situations with particular reference to cyclone devices for which some reference data already exists. In addition, LDV measurements have been made inside several of these devices and the excellent agreement between measured and predicted absolute flow variables has indicated that the model is ready to be applied in the combustion situation. Coupled with this development work has been the objective of making the program both interactive and suitable for use by people of limited training. As a result there has evolved a highly interactive code, many parameters of which can be changed in real time, and which has become essentially problem independent. As a result, the geometry to be solved is specified by the definition of prints on a 3-dimensional grid depending on whether the point is a wall, inlet or outlet etc.

There are thus several areas of work which contribute to the evolution of this study and these are shown in their inter-relation in Figure 1.

Part of the work of the past period has been concerned with residence time measurement, since this is a function which can be predicted from the flow field, and residence time distribution functions have been measured for a number of different tracer input positions in a gas turbine can. By incorporating the effect of turbulence within each cell of the combustor, the corresonding functions have been calculated for a large number of gaseous bubbles by using the droplet trajectory part of the algorithm. These results are shown in Figure 2 where it can be seen that for the input positions used, on the axis and through the inlet ports, the residence function shape is generally well reproduced. The inputs of the primary zone however indicate a relative time shift to the peak of the distribution and it remains to be seen to what extent the turbulence model used (k-ε) is responsible for this.

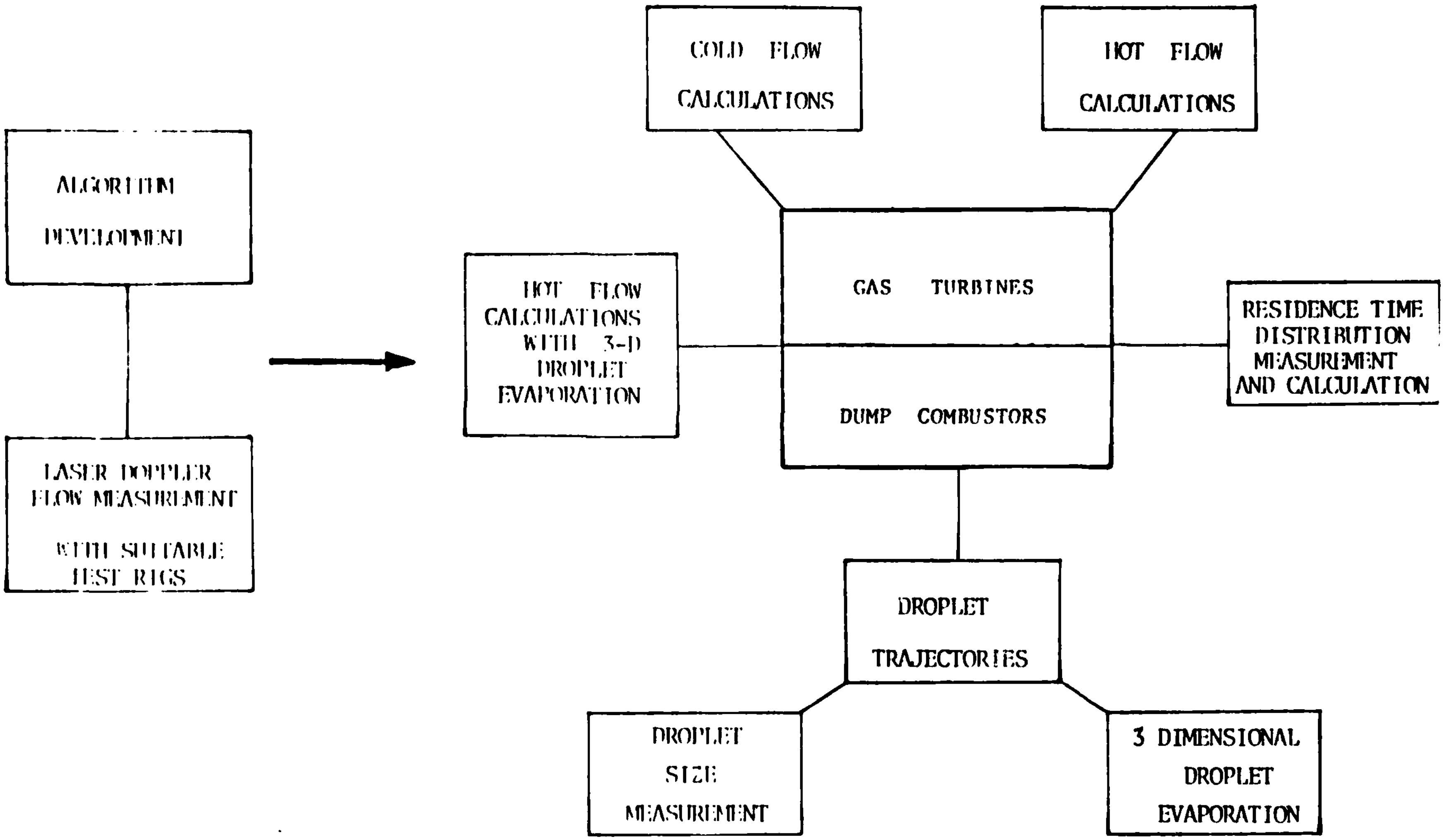


FIGURE 1 DEMONSTRATION OF THE ELEMENTS CONTRIBUTING TO THE PROGRAM AND THEIR INTER-RELATIONSHIP

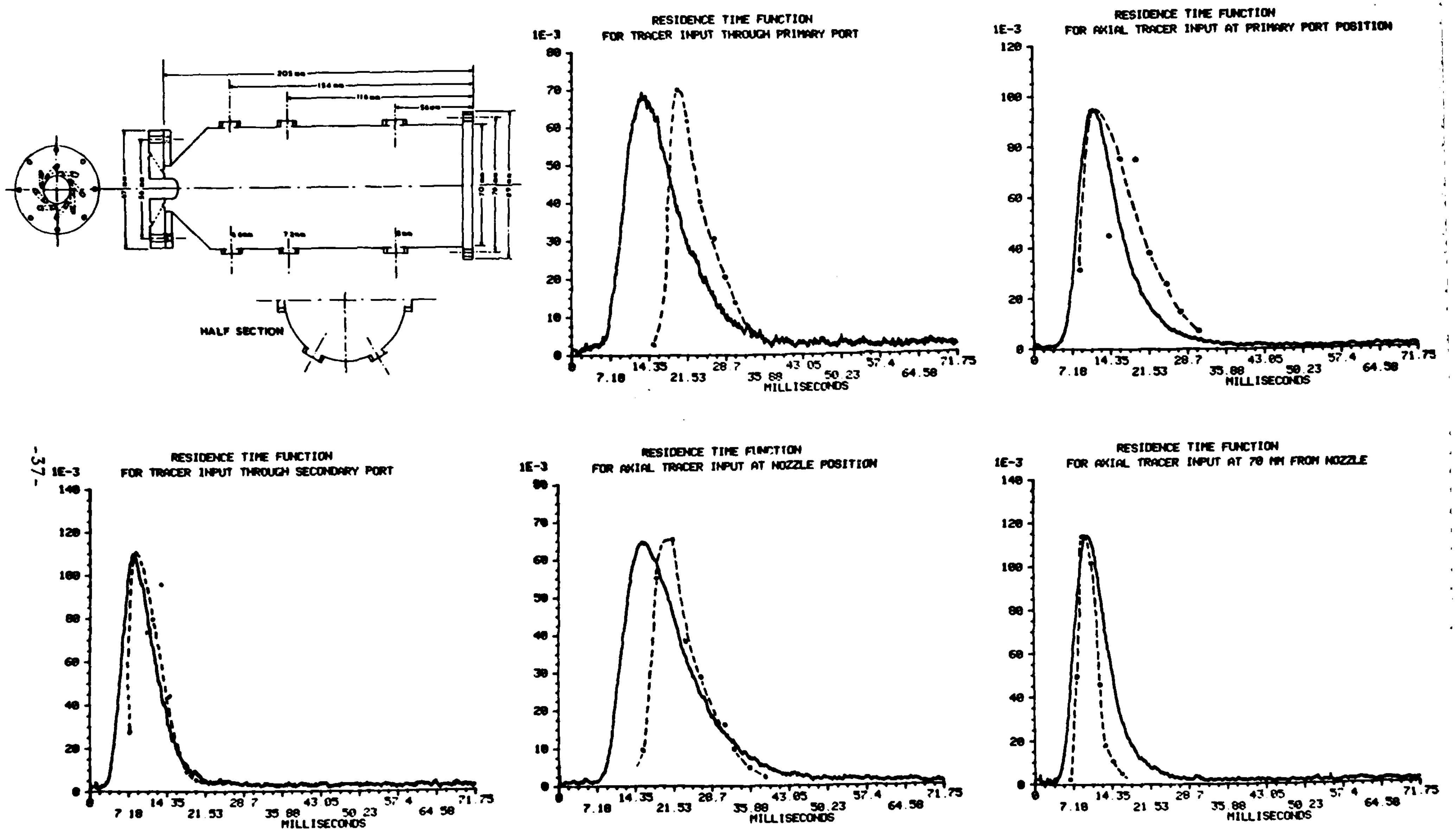


FIGURE 2 COMPARISON OF MEASURED AND CALCULATED RESIDENCE TIME FUNCTIONS AT VARIOUS TRACER INPUT POSITIONS FOR THE GAS TURBINE CAN SHOWN.

'Turbulent Combustion Modelling and Experiments'
(AFOSR Grant 81-0111)

K.N.C. Bray
(To be presented by G.M. Lilley)

Department of Aeronautics and Astronautics
University of Southampton
Southampton SO9 5NH
England

Abstract

The research is concerned with the modelling of turbulent, ducted, premixed combustion in dump combustors. Experiments are reported which allowed turbulent mass transport to be studied in a simulated dump combustor flowfield.

Previous work on gradient or eddy viscosity transport models, which are widely used in flow field predictions, has shown only partial experimental confirmation and this only when the flow is cold and of constant density. In flows involving significant heat release, large density fluctuations are observed which lead to strong interactions between the combustion and the turbulent flow field. Recent theoretical studies have shown that with premixed burning a second order closure is possible which does not invoke a gradient transport assumption. New turbulent transport mechanisms are thereby identified which lead to turbulent fluxes in the counter-gradient direction. It is thus found in a weakly-sheared turbulent flow that turbulent transport is dominated by the interaction between the mean pressure gradient and density inhomogeneities within the flow, and not by a gradient or eddy viscosity mechanism. We find that low-density, fully-burnt gas packets are preferentially accelerated by the pressure gradient in contrast to the slower moving high-density unburnt reactant. This relative motion between the burnt and unburnt gases leads to a turbulent flux of product in the sense of the decreasing pressure; in the flows studied, this direction is opposite to that predicted by gradient transport theories. The relative motion also leads to turbulence generation.

However, to obtain experimental confirmation is an exacting task, in spite of progress with optical diagnostics which permit the simultaneous determination of velocity and a scalar variable characterising the mixture state. Some experimental confirmation of the mechanisms described above has been obtained from studies of open, premixed flames of the Bunsen type. The present study, using the combustion rig illustrated in Fig.1, which simulates part of the flowfield of a dump combustor, seeks to investigate the turbulent scalar flux in a ducted burner under realistic conditions. Combined laser Doppler anemometry and Mie scattering are used to determine simultaneous velocity and density, from which the turbulent mass flux is calculated.

In ducted combustors, the externally impressed mean pressure gradient is much greater than observed in an open flame and hence enhanced effects are anticipated. The research therefore centres on two important features of the combustion processes, namely, turbulent transport and turbulence production due to a mean pressure gradient. These processes occur, and are important in many practical high intensity combustors but are neglected by all turbulent combustion models with the exception of the work described here.

The combustion rig, which is of conventional blow-down design, has an uncooled working section 71cm long. It is supplied with a homogeneous propane-air mixture which is spark ignited. The flame is stabilised by a rearward facing step 1.25cm high. A particulate seed (secondary air flow approximately 1% by volume) of dense smoke, generated from the room temperature reaction of $Ti\ Cl_4$ and moist air, is introduced upstream of the contraction. The smoke is well-mixed with the combustible mixture so that non-uniformity of seeding is small. The mean particle size of the $Ti\ O_2$ smoke is estimated to be 0.2μm. Axial velocity is measured with a forward scatter (dual beam) LDA system using a 25 mW He-Ne laser and Doppler signal processing by a frequency tracker. The LDA fringe volume has characteristic dimensions of 0.2mm by 1.2mm. The same photomultiplier signal, with the Doppler modulation removed, is used to provide a simultaneous measure of local density. The density signal is found to be strongly bimodal, indicating the existence of regions of unburned and fully-burned gas separated by thin reaction zones. Because of this property, the density signal identifies the presence of unburned or fully-burned gas, permitting the collection of separate "conditioned" velocity statistics for unburned and fully burned gas packets.

The analogue velocity data, both continuous and piecewise, following this scalar conditioning of the velocity into unburnt reactant and burnt gas contributions, has been analysed using a Hewlett Packad HP 3721A correlator sampling at 3kHz and the probability density functions (pdfs) have been obtained for the unburnt and burnt gases. Fig.2 shows typical results for the velocity pdfs with and without conditioning. It is evident that the method of conditioning has not introduced significant bias into the interpretation of the results. The conditioned pdfs are nearly Gaussian and are significantly displaced in the turbulent flame zone. Thus, the total pdf is highly skewed and in some cases bi-modal.

In the present experiments the mean speed of the unburnt gas ahead of the flame is 18.5 m/s and the corresponding rms turbulent velocity is 0.62 m/s. Strong counter-gradient diffusion is observed and the maximum velocity at which the reactant and product packets are moving through each other is $u_p - u_r = 5.2$ m/s at $\tilde{c} = 0.24$ ($\tilde{c}$ is the Favre-averaged progress variable).

It is found that the experimental data are bounded by theoretical estimates based on the analysis of oblique planar flames with and without confinement. In addition, using the assumption that counter gradient diffusion is driven by the mean pressure gradient, a scaling law is derived which reconciles the present data with those obtained in unconfined flames.

It is concluded that turbulent transport and turbulence production due to this new mechanism, which is related to the mean pressure gradient, are important processes which must be included in models for dump combustors and other practical systems. Further experiments are urgently required in support of this modelling.

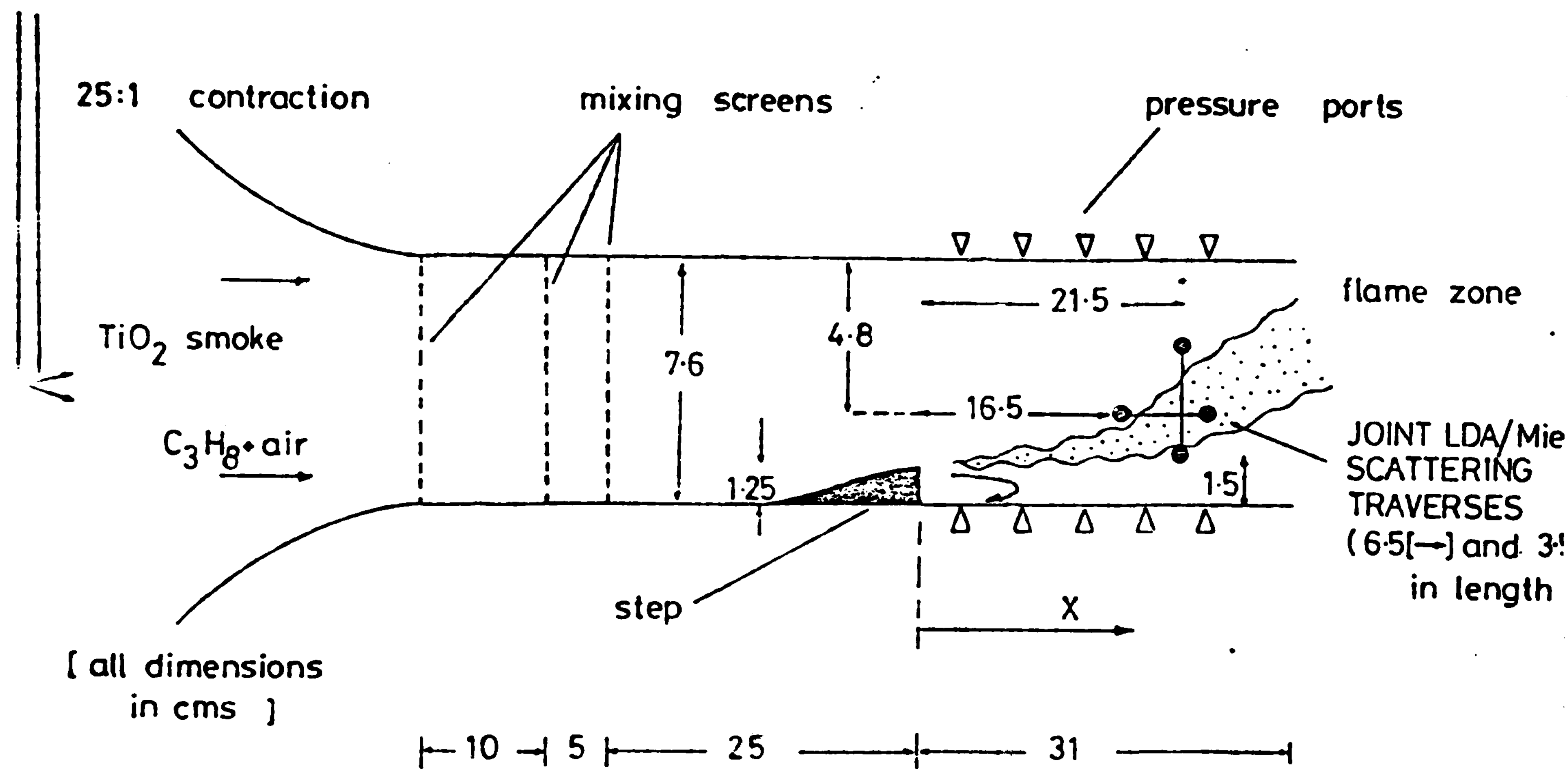


Figure 1 Duct geometry and experiment configuration.

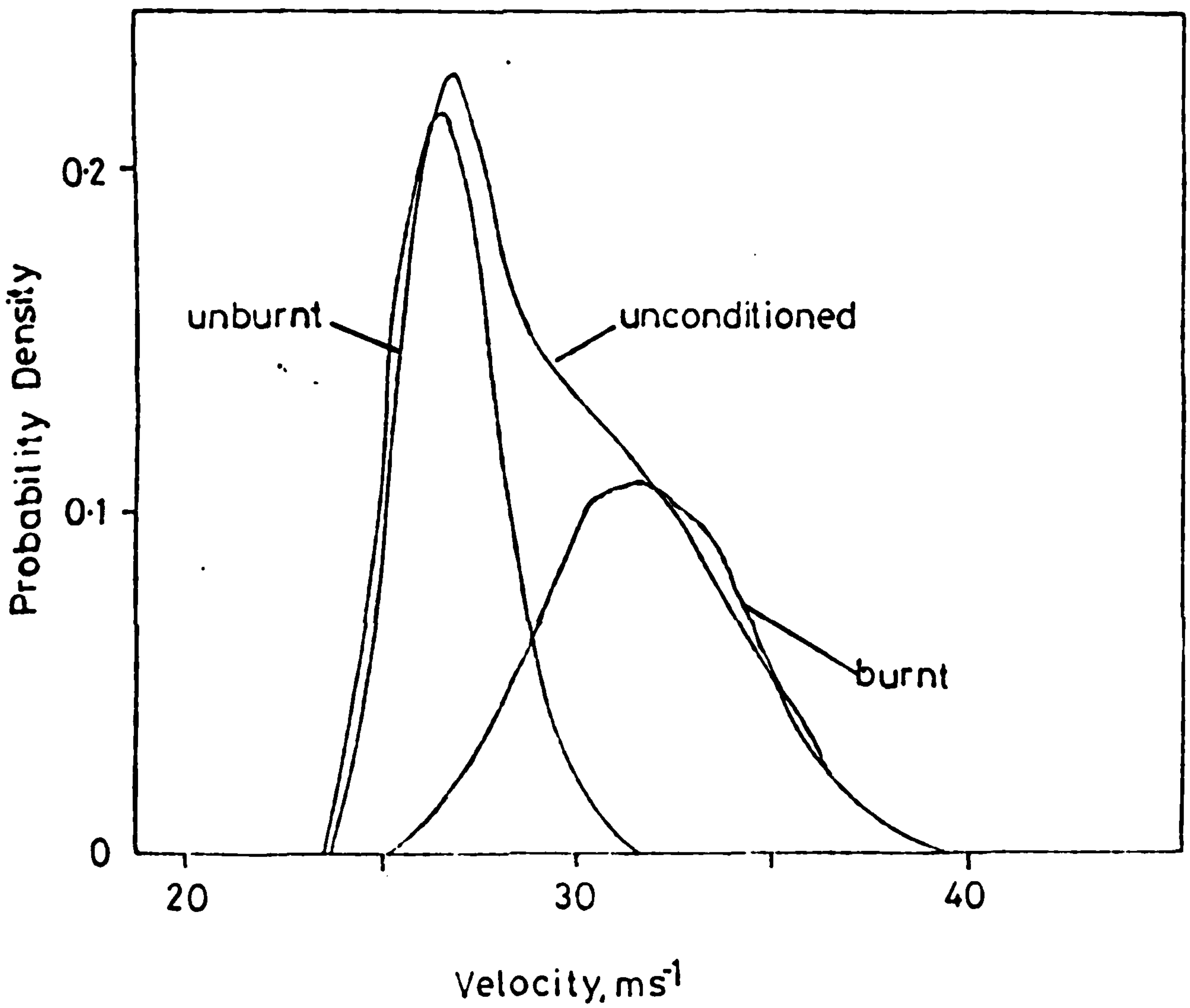


Figure 2 Probability Density Functions — For Velocity (i) unconditioned (ii) unburnt and burn

$\tilde{c} = 0{\cdot}24$: $\bar{u} = 29{\cdot}1$ m/s : $\bar{u}_p = 31{\cdot}7$ m/s : $\bar{u}_r = 26{\cdot}5$

CHEMICALLY REACTING TURBULENT FLOW

William M. Pitts, Takashi Kashiwagi, and Howard R. Baum

Center for Fire Research
National Bureau of Standards
Washington, DC 20234

This is a new long-term program, partly supported by AFOSR starting in FY 83, which is designed to provide an improved understanding of the complex coupling mechanisms which occur between the aerodynamics and chemical heat release in chemically reacting turbulent flows. Both experimental and theoretical studies are to be performed. The experimental study is to provide a wide data base for empirically describing turbulent behavior and the results will serve as benchmarks for the models which are developed.

Most past studies of chemically reacting turbulent flows have focused on complex reaction systems where the actual chemical reactions involved are difficult to predict and for which kinetic rate parameters are unavailable. In these cases, it is extremely difficult to unravel and characterize the highly nonlinear coupling of chemical heat release and aerodynamics.

Figure 1 includes a brief description of our approach to this problem. The experimental study is designed to be performed in separate stages. Initially, the effects of differences in density of a gas jet and its surroundings will be characterized for a simple flow system. A similar study will investigate temperature effects. These measurements are necessary since it is at present impossible to predict the effects of changes in these parameters on turbulent mixing. Once the effects of density and temperature differences are characterized, modifications in flow behavior due to chemical reaction will be investigated. A well-defined, simple chemical reaction having a known heat release and kinetic properties will be chosen. Since both the flow system and chemical reaction are well-characterized, it will be possible to isolate the effects of coupling the two processes.

During FY 83 the effects of density differences on turbulent mixing will be investigated. In order to characterize changes in flow behavior arising from differences in jet and surrounding gas densities, a wide range of flow properties will be determined. A diagnostic technique is currently being developed to allow simultaneous real-time measurements of concentration and velocity in a simple binary gas flow. This new method combines the use of laser Rayleigh light scattering for concentration measurements and a concentration-corrected hot-wire anemometer for velocity determination. Fig. 2a shows preliminary results for the real-time behavior of concentration and velocity in the intermittent flow region of a methane jet exhausting into a slow coflow of air. The effects of density differences on jet parameters such as spatially resolved average concentration and velocity, concentration and velocity

2

intensities, autocorrelations and cross correlations of velocity and concentration, and concentration and velocity intermittency will be determined.

Theoretical development of models to predict turbulent behavior is scheduled to begin in late FY 83 and will proceed in a systematic and logical way in analogy with the experimental approach (e.g., modifications in turbulent mixing behavior due to density effects will be studied initially). The model will attempt to combine both Eulerian and Lagrangian approaches such that the equations of motion for the fluid are solved approximately. Large scale eddy motion is to be calculated numerically using finite difference approximations to solve the time dependent equations of motion. Once these solutions are available, a Lagrangian-type analysis will be performed to follow the behavior of mixing and chemical reactions on smaller turbulence scales. This approach to the problem is unique and offers the promise of generating time-dependent solutions which can be compared with experimental results. Most current models of turbulence average the equations of motion and assumptions must be made concerning the forms of additional equations describing turbulent transport of mass, momentum, and energy. Due to the averaging inherent in these models, comparison with the actual fluctuation behavior of turbulent systems is difficult.

A similar modeling approach to that described above is currently being used at the National Bureau of Standards to investigate the motion of smoke and hot gases in an enclosure. Finite difference methods are used to calculate the plume behavior. Lagrangian information concerning densities of smoke particles are calculated by introducing up to ten thousand markers in the flow field. Fig. 2b shows a plot of soot density calculated in this way.

PROBLEM

- IMPROVE FUNDAMENTAL UNDERSTANDING OF NONLINEAR COUPLING OF CHEMICAL HEAT RELEASE AND AERODYNAMICS IN CHEMICALLY REACTING TURBULENT FLOWS

APPROACH

- SIMULTANEOUS EXPERIMENTAL AND THEORETICAL EFFORT
- ISOLATE EFFECTS DUE TO DENSITY, TEMPERATURE, AND CHEMICAL REACTION ON TURBULENT BEHAVIOR
- INVESTIGATE SIMPLE, WELL-DEFINED FLOW GEOMETRY
- STUDY SIMPLE CHEMICAL REACTION WHICH IS WELL-CHARACTERIZED AS TO CHEMICAL AND KINETIC BEHAVIOR

NEEDS

- DEVELOPMENT OF NEW DIAGNOSTIC TECHNIQUES
- GENERATION OF A WIDE EXPERIMENTAL DATA BASE OF DETAILED MEASURES OF FLOW BEHAVIOR UNDER VARYING CONDITIONS OF DENSITY, TEMPERATURE, AND CHEMICAL REACTION
- DEVELOPMENT OF MODEL FOR TURBULENT FLOWS EMPLOYING A COMBINED EULERIAN AND LAGRANGIAN APPROACH

Figure 1

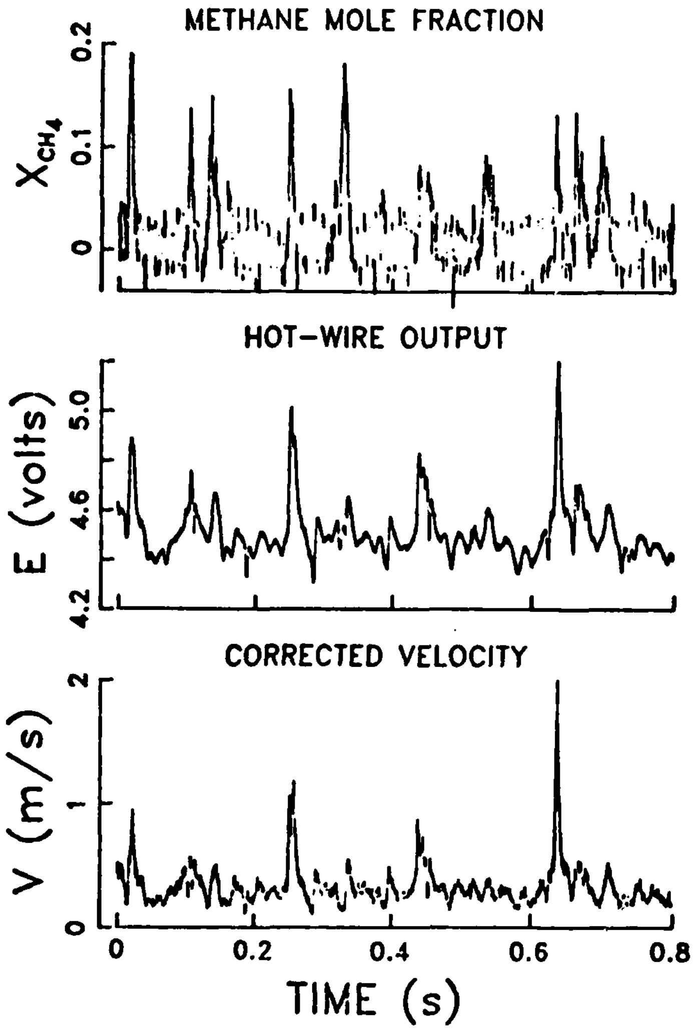


Figure 2A Simultaneous recordings of time behavior for Rayleigh scattering intensity and hot-wire output in the intermittent region of a methane-air jet. The calculated velocity behavior is also included.

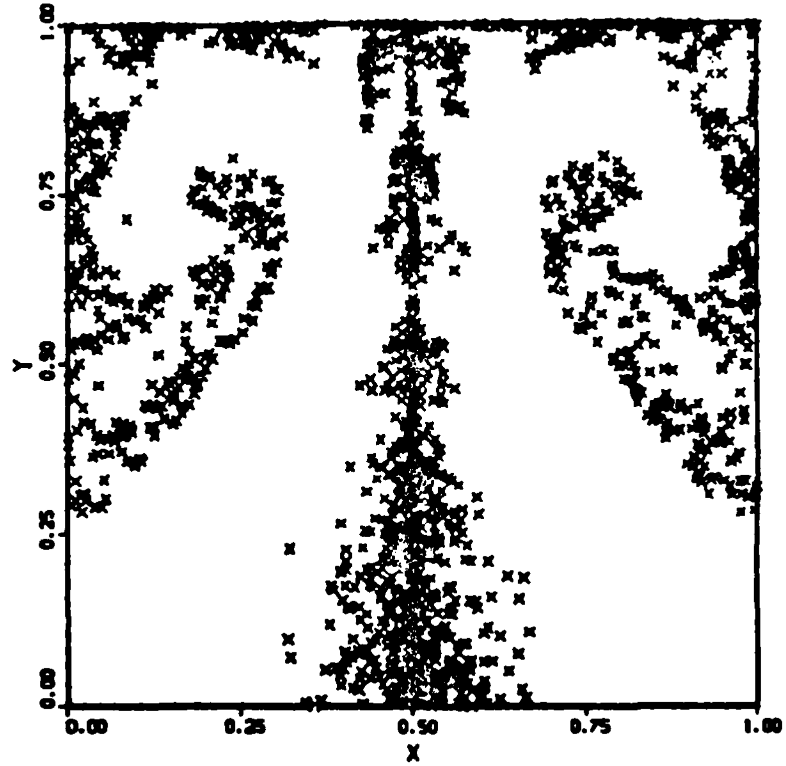


Figure 2B Calculated smoke particle density for a buoyant plume within an enclosure.

COMBUSTION IN HIGH SPEED AIR FLOWS (F49620-80-C-0082)

Raymond B. Edelman and Philip T. Harsha

Science Applications, Inc.
Combustion Science and Advanced Technology Department

9760 Owensmouth Avenue
Chatsworth, CA 91311

The purpose of this research is the investigation of fundamental mechanisms involved in combustion in high-speed air flows through the development of realistic combustion and combustor models and comparison of the predictions of these models with experimental data. The modular combustor model has been a major focus of the research partly because it provides a means for incorporating detailed analytical treatments of each of the processes occurring in high-speed combustion and, most importantly, the coupling between these processes. Liquid- and slurry-fueled combustion processes are being investigated for gas turbine, ramjet, and ducted rocket combustors.

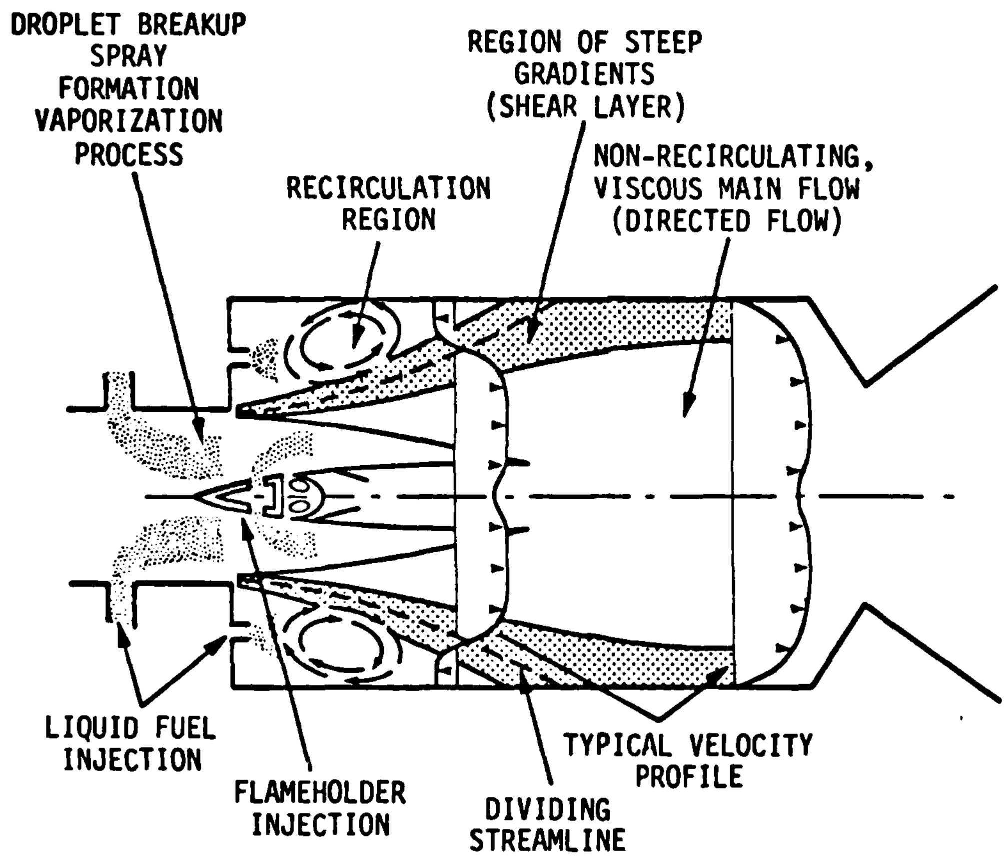
Characteristics of the modular model approach are outlined in Figure 1. The basic concept involves the subdivision of the combustor flowfield into characteristic regions which, for the axisymmetric sudden-expansion configuration includes the large-scale recirculation region, the nonrecirculating viscous main flow, and the shear layer which both separates and provides the coupling between the other two regions. Each of these regions is computed in detail using appropriate modeling, allowing the detailed analysis of key processes such as turbulent mixing, chemical kinetics, fuel injection, spray formation, vaporization, and mixing, and heterogeneous mixing processes involving both droplets and particles as appropriate for slurry fuels. Although shown for the axisymmetric sudden expansion, the modular model concept is extendible to more complex geometries, such as the three-dimensional ducted rocket configuration. It should be noted that the use of the model requires an aerodynamic characterization of the flowfield; this can be obtained from experimental data or through use of an elliptic aerodynamic model depending on available experimental data.

An important element of the combustion process in ramjets and gas turbine engines is liquid fuel (or slurry fuel) spray dynamics and combustion. To account for this process, the modular model formulation is being modified to incorporate a detailed spray dynamics model and a droplet/particle combustion formulation. Figure 2 depicts current results in each of these areas, showing a comparison with experimental data for spray vaporization and mixing and for boron particle combustion. The boron particle model successfully predicts the burn times experimentally measured for particles of sizes ranging from 1 μm to 30 μm and, importantly, also predicts the change from kinetically controlled combustion to diffusion controlled combustion that is expected to take place for particles of diameters greater than 30 μm. The spray transport and vaporization model provides a good prediction of the mixing rate observed in a spray jet flow, and provides detail, such as the relative proportions of liquid-phase and vapor-phase fuel, and the distribution of spray droplet sizes at each point in the flow, that is unavailable in present data. Combination of these two advanced formulations within the modular model will provide a detailed analytical description of the processes occurring in a ramjet combustor operating on boron slurry fuel. No model for this application currently exists.

Development of models for boron slurry and spray combustion phenomena requires a base of well-characterized experimental data. Such a data base is being developed in a series of experiments being carried out, jointly with this program, by Dr. Klaus Schadow at the Naval Weapons Center (NWC). The experiments at NWC encompass gas-phase mixing and combustion, liquid spray combustion, particle-laden gas-phase combustion, and slurry combustion. Through a close interaction with analytical model development, these experiments are providing a hierarchy of experimental results for flows with progressively increasing complexity which are nevertheless well-characterized throughout. Additionally, a set of highly-instrumented spray combustion experiments are being planned to be carried out in the SAI-Chatsworth Combustion Laboratory facility. These experiments will provide the detailed data necessary to complete the development of the spray dynamics modeling approach.

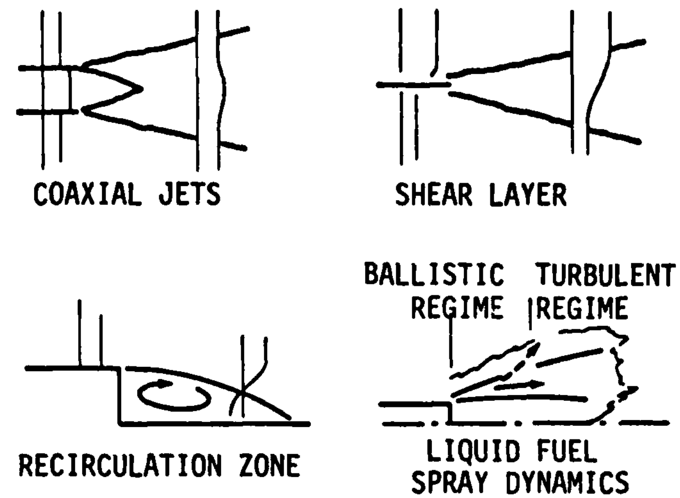
STEADY-STATE AIRBREATHING COMBUSTION MODULAR MODELING APPROACH

- ANALYSIS AND PREDICTION OF COMBUSTOR CHARACTERISTICS
- DETAILED FLOWFIELD MEASUREMENTS TO GUIDE MODELING



SUDDEN-EXPANSION (DUMP) COMBUSTOR

- ISOLATE MECHANISMS/PROCESSES
- MODEL EACH ELEMENT IN DETAIL
- COUPLE ELEMENTS THROUGH BOUNDARY CONDITIONS



ELEMENT	TREATMENT
Parabolic Directed Flow	Finite Difference Solution
Shear Layer	Simplified Linear Model
Recirculation Zone	Perfectly Stirred Reactor
Liquid Fuel Spray Dynamics	Two-Phase Flow/Droplet/Particle Transport Model

Concept not limited to these formulations.

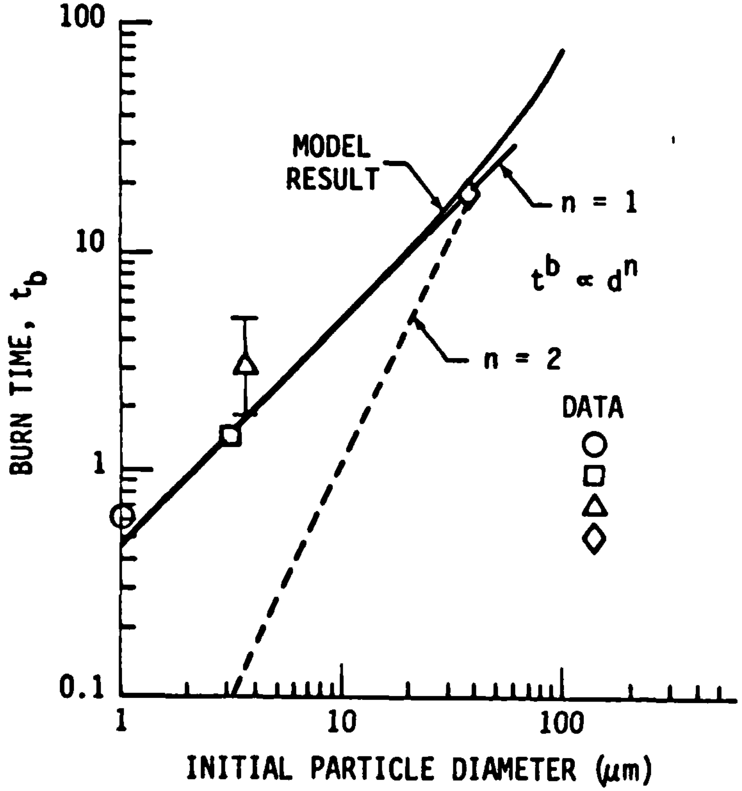
ELEMENTS OF MODULAR MODEL

Figure 1

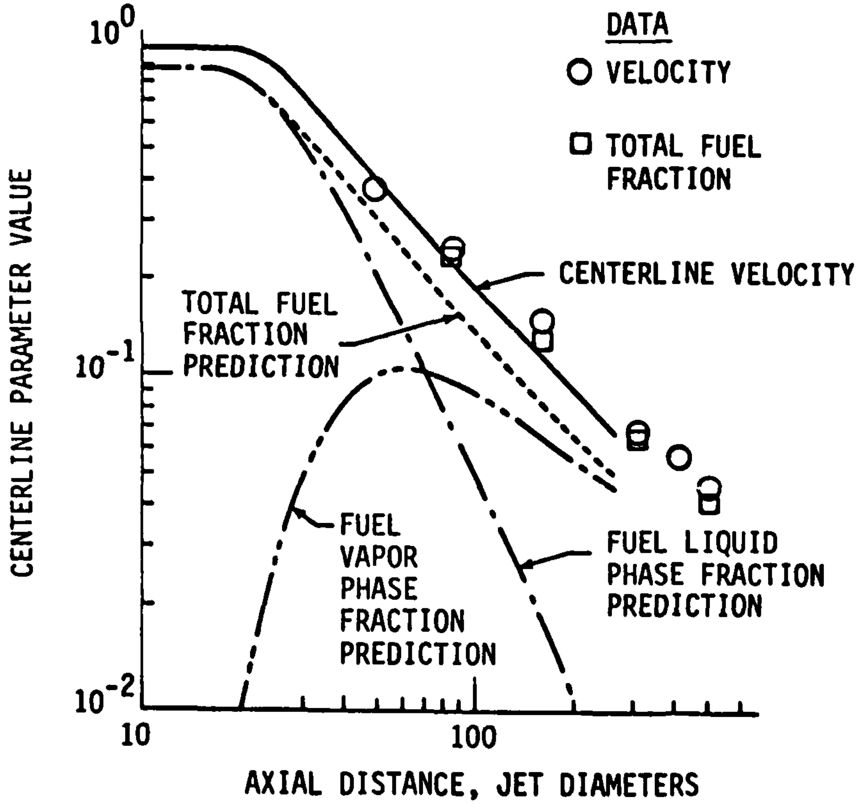
AIR FORCE BASIC RESEARCH

ACHIEVEMENT

IMPROVEMENTS TO MODULAR MODEL IN KEY AREAS
OF SPRAY TRANSPORT/VAPORIZATION AND BORON COMBUSTION



BORON PARTICLE COMBUSTION MODEL



SPRAY TRANSPORT/VAPORIZATION MODEL

COMBINATION OF MODELS WILL PROVIDE DETAILED

DESCRIPTION OF SLURRY COMBUSTION PHENOMENA IN RAMJETS

Figure 2

CHEMICAL REACTIONS in TURBULENT MIXING FLOWS

H.W. Liepmann, J.E. Broadwell, P.E. Dimotakis and A. Roshko

Graduate Aeronautical Laboratories
California Institute of Technology
Pasadena, California 91125

This is an investigation of the fundamental mechanisms of turbulent mixing and combustion, including the effects of heat release, Reynolds number and Schmidt number. The work is composed of three parts: an experimental program, the development of analytical models, and the development of special instrumentation and diagnostics.

Work this last year concentrated on a low heat release investigation using combustion of hydrogen and fluorine in a turbulent, two-dimensional mixing layer at low reactant concentrations (low heat release) for a wide range of reactant equivalence (concentration) ratios. These highly exothermic chemicals react spontaneously to form hydrogen fluoride, obviating flame holders and igniters. Our results offer new insight into the combustion process and provide a reliable data base to which computational and/or analytic models can be compared. Fig. 1a shows the time-resolved temperature measured at eight locations across the shear layer. These time traces can be understood in terms of the large scale structures in the flow, and yield the mean temperature (or chemical product) profiles when integrated as a function of time (Fig. 1b). Note that the adiabatic flame temperature is not achieved, on average, at any location. Also shown are the highest and lowest temperature recorded by each probe. These results are at variance with conventional gradient diffusion models, as are the mean profiles (Fig. 1d) for the range of equivalence ratios investigated. Fig. 1c shows that the amount of product formed in the layer increases monotonically with equivalence ratio and reaches an asymptotic value at an equivalence ratio of approximately 6. Finally, a significant result is that there is 35% more product formed in a gas than a liquid, implying that the molecular diffusion coefficient plays an important role in turbulent mixing. These results, including Schmidt number effects, can be rationalized in terms of a simple model proposed by Broadwell & Breidenthal, developed under this contract. Future investigations in this area include measurements at higher Reynolds numbers and increasing amounts of heat release. Additionally, the HF combustion facility is being instrumented with a high time and space resolution schlieren system to assist in the measurements at the higher temperatures.

Progress in other areas includes direct measurements of the probability density function (pdf) in a turbulent mixing layer using laser induced fluorescence, measurements of chemically reacting turbulent jets and the development of real time digital image data acquisition techniques for the purpose of measuring species concentration fields.

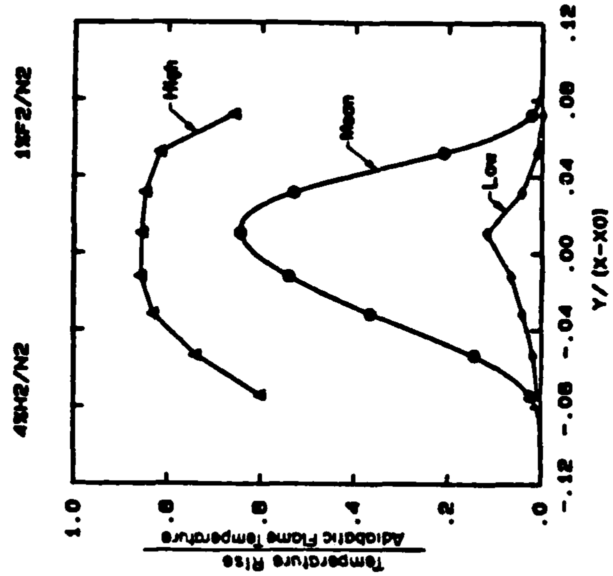


Fig 1b

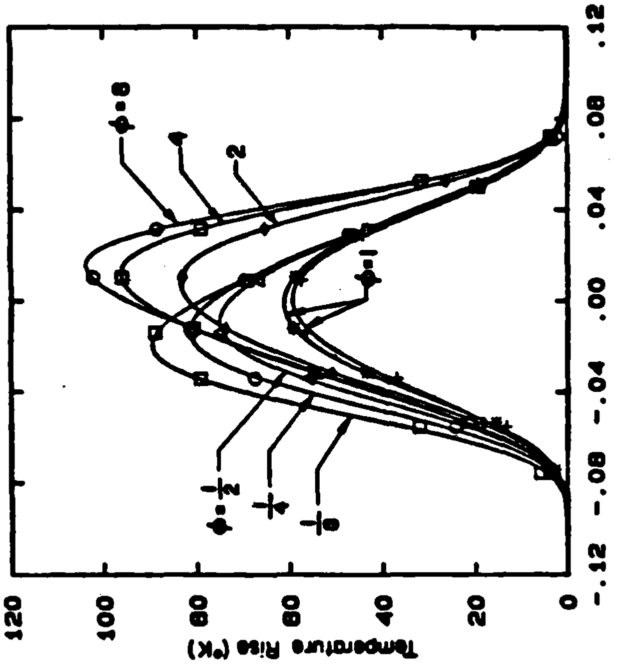


Fig 1d

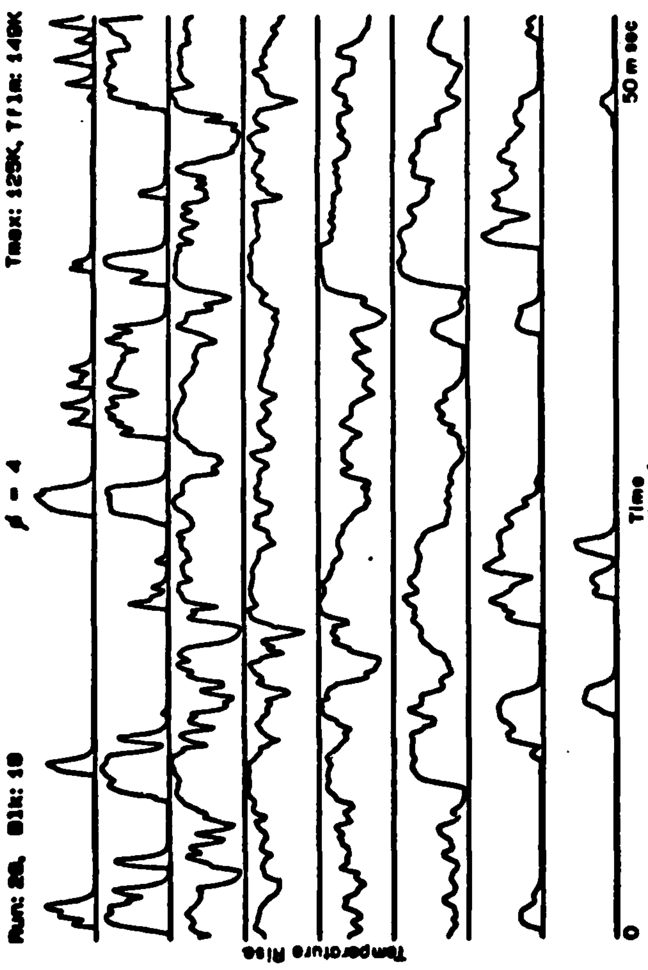


Fig 1a

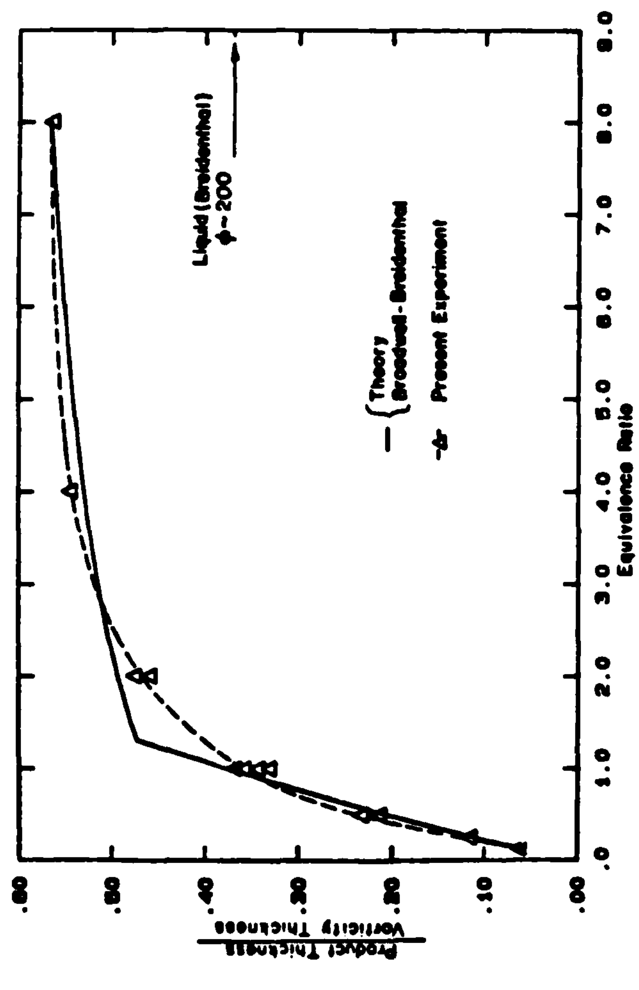
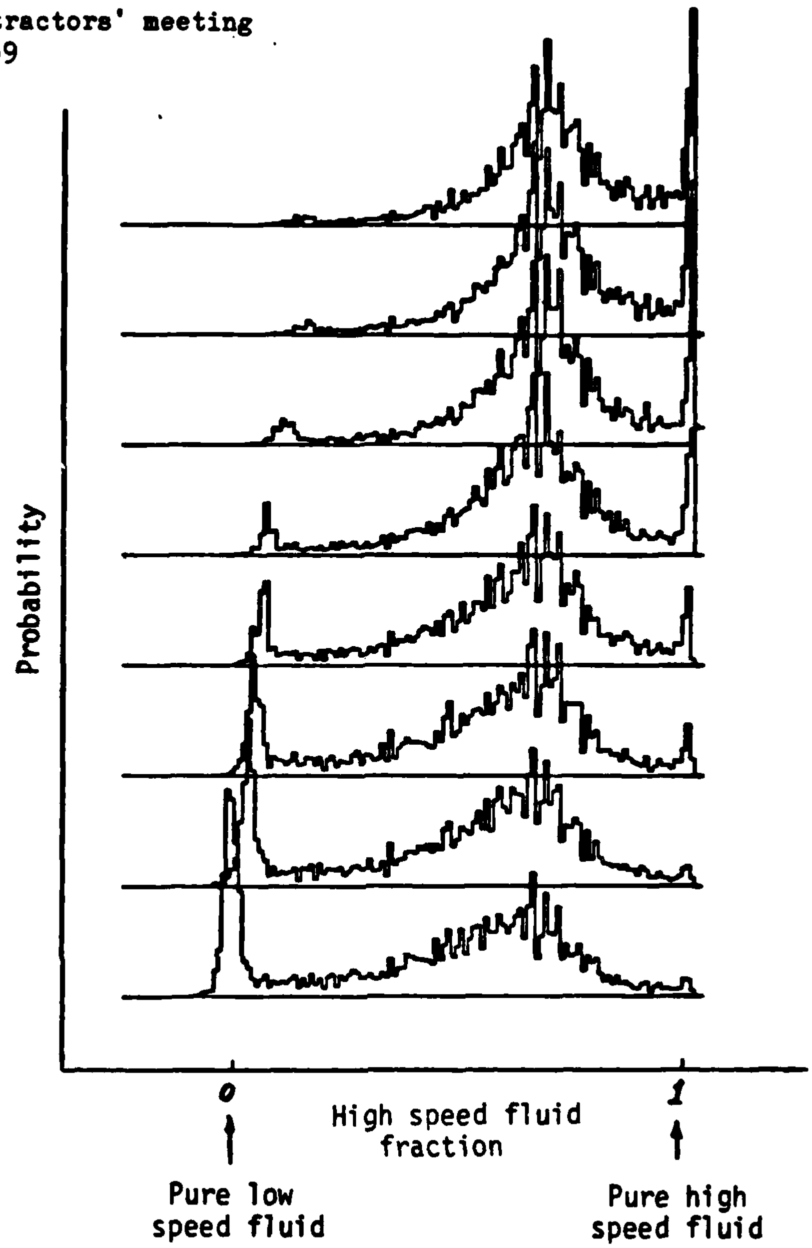


Fig 1c



Direct measurement of PDF of mixing in a plane shear layer using the laser induced fluorescence technique. The figure above shows the results (raw data) at eight different locations, uniformly spaced by 2.4 mm, extending over 0.8 of the local vorticity thickness of the mixing layer (velocity ratio $U_1/U_2 \simeq 2.65$, Reynolds number $\simeq 8200$).

Note that the composition of the mixed fluid is fairly uniform across the layer and that the PDF is asymmetric, with an excess of high speed fluid.

AFOSR Contract No. 82-0266

LARGE EDDY STRUCTURES IN TRANSITIONAL AND TURBULENT FLAMES

Norman Chigier

Department of Mechanical Engineering
Carnegie-Mellon University
Pittsburgh, PA 15213

The purpose of this research is the investigation of the fundamental mechanisms involved in the formation, development and subsequent history of large eddy structures in jet flames. The study includes identification and characterization of large eddy structures moving through flames and establishing their relation to fuel-air mixing, interface burning, entrainment patterns, residence times, macro and micro-mixing processes.

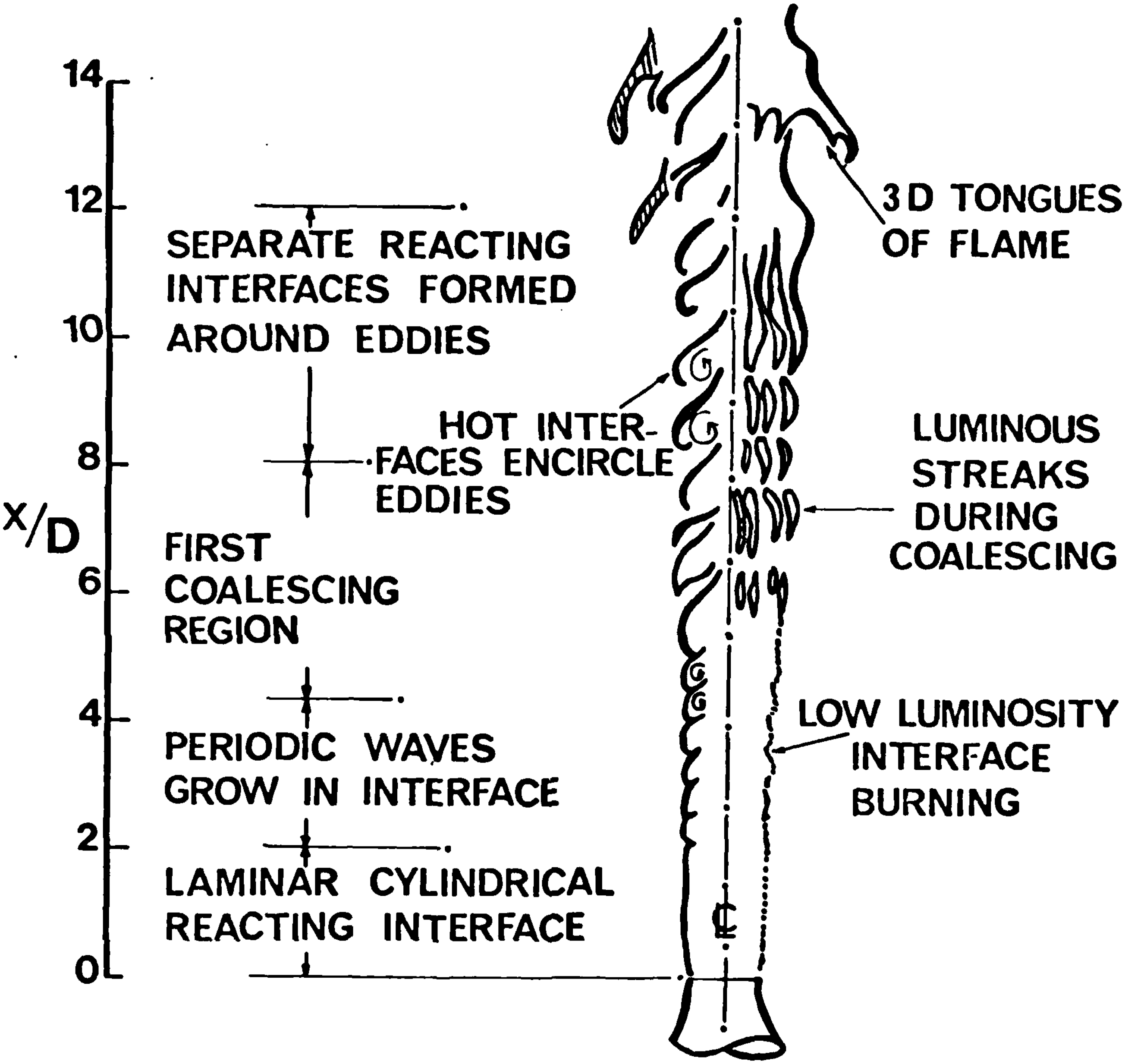
The area of investigation in the near-flow field of a jet flame is shown in Fig. 1. For exit Reynolds numbers of the order of 10^4 an initial laminar cylindrical interface is formed at the nozzle exit. Instabilities develop and periodic waves grow resulting in development of luminous streaks and formation of separate reacting interfaces surrounding individual large eddies. The detailed investigation of these phenomena, initially studied at the University of Sheffield, will be continued at Carnegie-Mellon University.

Initial detection of characteristic organized large vortex structures will be made by high speed color Schlieren motion picture photography. Special visualization techniques will be used to show the three dimensionality of the structures and their movement. Means will be sought to relate the streamwise streaks to a mechanism for regenerating primary structures by a Kelvin-Helmholz instability. The low frequency highly organized ring vortices formed in the outer regions of the jet will be examined and measured carefully.

The main approach in the study is the utilization of accurate and reliable, high frequency response, instrumentation with high spatial and temporal resolution. Conditional sampling and correlating using computer data processing techniques will be used to yield information on flow structure. The main experimental techniques that will be used are: laser schlieren cine photography, laser anemometry, ionization probes and microthermocouples. Signals from combinations of probes will provide simultaneous acquisition of time histories by microprocessor followed by data processing to measure the structures and histories of large eddies and the interface burning regions associated with them.

Some of the fundamental questions that will be addressed are: (i) What is the effect of change of initial boundary conditions at the burner exit on flow structure in the jet flame? (ii) Why does change in equivalence ratio in partially premixed flames cause significant changes in flow structure in the flame? (iii) What is the triggering mechanism and nature of instabilities generated in the near flow field?

This research is related to the U.S. Air Force mission of improving the design control and lifetime of advanced air-breathing engines where it is recognized that large eddy structures of unmixed or poorly mixed fuel can result in development of nonhomogenities within the concentration and temperature flow fields. Stoichiometric mixture ratios can form at the burning interfaces of individual eddies; when these impinge on combustor liner walls they can lead to deposition of carbon and eventual burn-out at local hot spots on the wall.



14
12
10
8
6
4
2
0
X/D
SEPARATE REACTING INTERFACES FORMED AROUND EDDIES
HOT INTER- FACES ENCIRCLE EDDIES
FIRST COALESCING REGION
PERIODIC WAVES GROW IN INTERFACE
LAMINAR CYLINDRICAL REACTING INTERFACE
3D TONGUES OF FLAME
LUMINOUS STREAKS DURING COALESCING
LOW LUMINOSITY INTERFACE BURNING

APPLICATION OF MULTI-DIMENSIONAL MODELING TECHNIQUES TO THE DESIGN AND DEVELOPMENT OF GAS TURBINE COMBUSTORS

H. Mongia

Garrett Institute Engine Company

ABSTRACT NOT AVAILABLE

FUNDAMENTAL COMBUSTION STUDIES WITH ALTERNATIVE FUEL SPRAYS UNDER HIGH AIR TEMPERATURE AND PRESSURE CONDITIONS

Co-Principal Investigators: James E. Peters, Herman Krier, Kevin Kim
University of Illinois at Urbana-Champaign
Urbana, IL 61801

OVERVIEW

Improved gas turbine combustion performance will require the effective utilization of alternative fuels and advanced combustor concepts. Therefore, further understanding of spray combustion processes such as evaporation and flame propagation is required. In pursuit of this goal, a program is described which features a high pressure (800 kPa) and temperature (900 K) non-vitiated air system to provide air at simulated gas turbine inlet conditions. A special fuel injection system designed to produce monodisperse sprays will be employed; polydisperse sprays will also be attainable.

Two primary experiments will be performed. The evaporation rate of sprays as a function of fuel type and inlet conditions such as pressure and temperature will be determined with optical techniques and physical collection schemes. In addition, flame propagation rates in fuel-vapor-air mixtures at high temperature and pressure will be measured. In conjunction with these measurements, a two-dimensional, two-phase, spray combustion model will be developed to compare with the experimental results.

GAS TURBINE/ALTERNATIVE FUELS COMBUSTION STUDIES

Alternative fuels derived from coal and oil shale sources have properties characteristically different from petroleum based fuels that can affect their use and performance as fuels in modern day turbo-jet engines. The use of such fuels by the Air Force or by civil aviation requires that appropriate understanding of the fundamental combustion processes be available.

The changes in fuel properties such as viscosity and volatility that often accompany alternative fuels can degrade engine performance through poor atomization and reduced evaporation rates. Therefore, experimental measurements are planned to quantify these effects in order to develop a sound basis for any necessary combustor design changes. These measurements will be supplemented with analytical models as a part of this research program.

In addition, the trend toward higher pressure ratio engines indicates the need for spray combustion studies at the elevated pressures and temperatures obtainable in the facility described below. Advanced combustor concepts also include variable mixing schemes and prevaporized/premixed combustors. Both techniques involve design tradeoffs and detailed studies are required to optimize, for example, the amount of fuel to be vaporized or the amount of air that can be added to the primary zone without significantly reducing ignition and flame stability limits. Consequently, the research program will include experiments that vary the degree of vaporization.

EXPERIMENTAL FACILITY

The air system that is available for this research is a large scale facility that is fed by two compressors (a Gardner-Denver and an Ingersoll-Rand) which can supply air flow rates of 1 kg/sec at 600 kPa (6 atm) continuously. The tank farm provides 115 m^3 of storage at pressures up to 800 kPa (8 atm) for airflow rates in excess of 1 kg/sec for limited duration tests.

The high pressure air is indirectly heated by a Trane Model DF-1050 heat exchanger which provides non-vitiated inlet air. Temperatures up to 900 K for air flow rates of 2.2 kg/sec are available from the heat exchanger, which is rated at 1.5 megawatts.

After being heated, the air will be metered by a standard orifice plate configuration and remotely controlled valves will provide independent control of air flow rates and pressure. A flow straightening section will be located immediately upstream of the test section to produce a uniform flow field in the combustor. Important features of the test section are illustrated in Fig. 1.

Downstream of the flow straightener, fuel is injected with the technique described below which will produce a uniform spray. Windows in the test section will permit spray characterization via photomicrography, LDV, and forward scattering measurements to determine drop sizes, number densities and velocities as a function of distance downstream of the fuel injector. Both the forward scattering system and the photomicrography equipment are presently available for this project.

Access to the spray will also be provided for a phase discriminating probe which will be used to determine the equivalence ratio at any point in the spray with respect to the total amount of fuel or the fuel in the vapor or liquid phase. This will provide an additional check on the optical measurements.

Further downstream, the mixture will be ignited and the flame spread will be observed with a Schlieren system and thermocouple measurements to determine flame speed as a function of drop size, vapor phase equivalence ratio and other run conditions. An important feature of the test section will be the variability of the distance between the fuel injector and igniter. For example, as the inlet temperature is increased, to maintain a constant amount of fuel in the vapor phase at the igniter, the distance between the igniter and injector will be decreased.

The experimental system described above will be capable of providing evaporation rate and burning rate data for sprays better characterized than previous work in terms of drop size, drop number density, and fraction of fuel evaporated and for practical ranges of temperature, pressure, and fuel type not obtained by other investigators.

In the proposed experiment, which initially requires mass production of monodisperse fuel droplets, both mechanical and electrical techniques will be considered for possible implementation. After an initial feasibility study, the more suitable of the two will be chosen. Design and construction of the fuel injector to be coupled to the combustion chamber can then begin. For this application, the fuel will be injected through a collimated hole structure, rather than the single orifice approach, to produce a "spray" of drops instead of a single array.

One such fuel injector design incorporating a collimated hole structure (CHS) is shown in Fig. 2. The operating principles of this injector system are as follows. First, fuel to be injected into the combustion chamber is pressurized and fed into the injector unit at a controlled flow rate. This flow rate, combined with the transparency of the CHS mounted at the injector exit end, determines the speed of the fuel jets emanating from the injector. The size and uniformity of these jets are controlled by holes in the CHS. Once the smooth fuel jets are formed in this way, then the piezoelectric transducer mounted onto the rear of the injector unit is activated, generating an acoustic wave which propagates along the length of the injector. It is this acoustic excitation that causes the fuel jets to break up into uniform droplets. By controlling the amplitude and oscillation frequency of the voltage applied to the piezoelectric transducer, one can produce a wide range of monodisperse fuel droplets, with the minimum achievable drop size dictated by the size of the holes in the CHS. An important feature implemented with this fuel injector design is that the cross-sectional area of the injector nozzle decreases exponentially toward the exit end, resulting in amplification of the acoustic wave due to an "acoustic horn" effect. This enhances the effectiveness of the acoustic excitation giving rise to the breakup of fuel jets into uniform droplets.

To produce fuel droplets smaller than the holes in the CHS, one can invoke electrohydrodynamic spraying by applying high voltages to the CHS. This and other possibilities, including various fuel injector designs, will be considered. By simultaneously employing more than one injector, it will also be possible to prepare a polydisperse fuel mixture. An important part of the fuel injector developmental work will, therefore, involve testing the multiple fuel injector concepts and studying the propagation and distribution of the fuel drops inside the combustor.

RESEARCH PROGRAM

The project is planned as a three year program. A major portion of the research effort in the first year is necessarily devoted to design and construction of the experimental apparatus. Consequently, only limited data are expected in the first year. The second year and third year of this work will involve detailed measurements of evaporation and propagation rates over a range of variables including air temperature, air pressure, equivalence ratio, fuel drop size, fuel injection velocity, and fuel type. Further along in the research, experiments with the complexity of a polydisperse rather than a monodisperse spray are envisioned.

In order to expand the utility of the experiments, it is planned that a comprehensive two-dimensional, two-phase reactive flow model will be developed, which can predict flammability characteristics as a function of spray character and fuel properties. In general, current analytical models do not solve the complex two-phase flow conservation relations by coupling the spray behavior to the gaseous flow field. We will not, therefore, resort to typical ad hoc corrections of the fuel spray processes in the reacting flow model to be developed.

FUNDAMENTAL SPRAY COMBUSTION STUDIES WITH ALTERNATIVE FUELS

University of Illinois at Urbana-Champaign

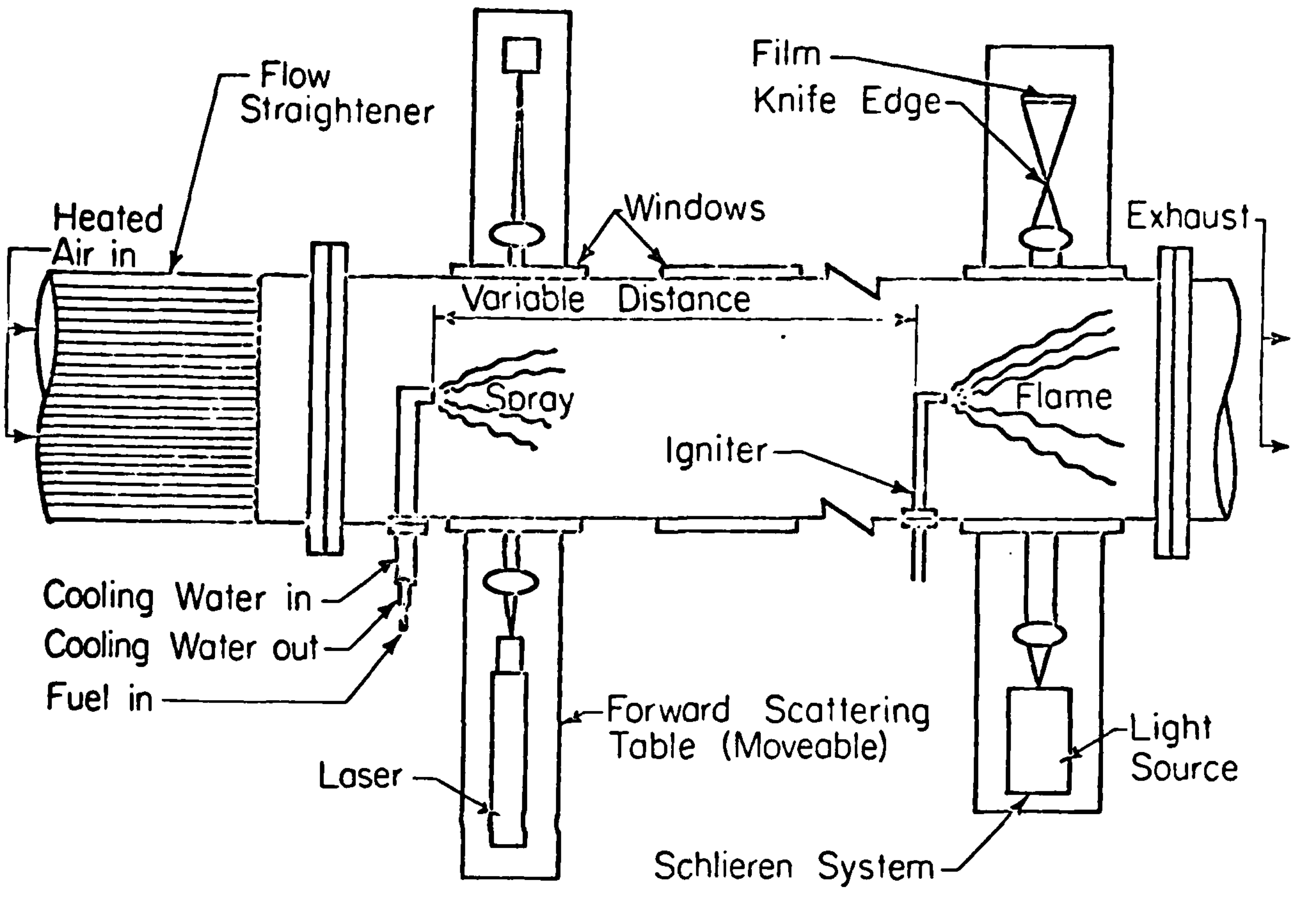


Figure 1

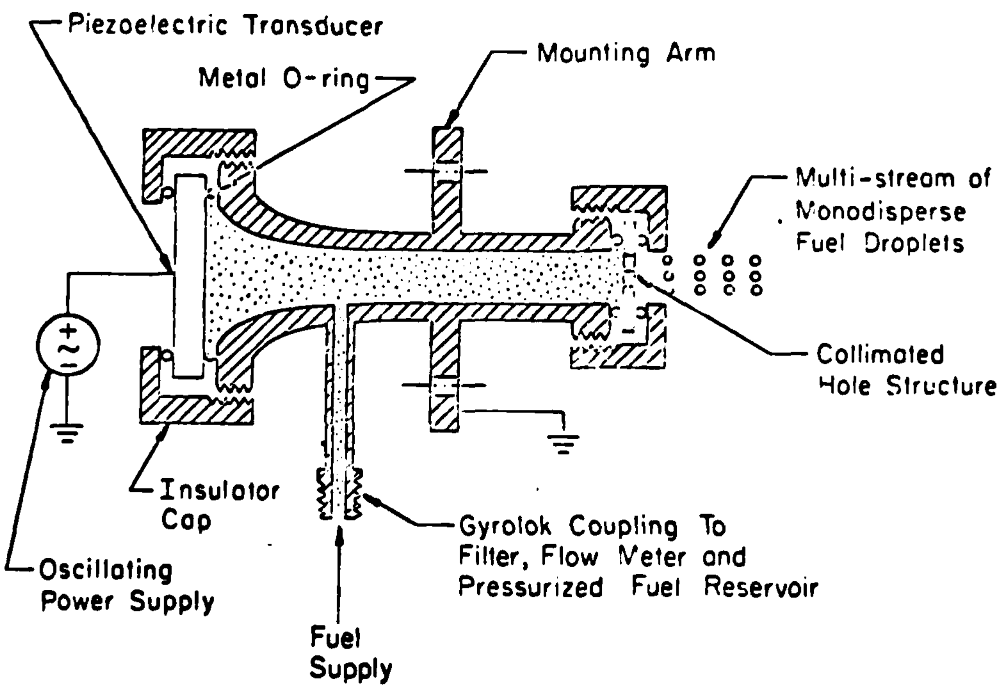


Figure 2

IONIC MECHANISMS OF SOOT FORMATION IN FLAMES

H.F. Calcote and D.B. Olson

AeroChem Research Laboratories, Inc.
P.O. Box 12, Princeton, NJ 08540

The objective of this program is to understand the mechanism of soot formation in flames and to interpret this mechanism in terms of soot formation in air-breathing engines. Understanding the mechanism by which soot is formed in combustion systems, especially the initial nucleation step, is one of the major problems in combustion research today. Most proposed mechanisms involve free radicals and acetylene reactions. Our approach assumes that chemi-ions play a key role in initiating the nucleation step and that the pool of free radicals and acetylenes is a source of neutral reactants for growing larger ions. A detailed mechanism is hypothesized, Fig. 1, which proceeds by a series of steps of continuously varying character from the formation of a chemi-ion to the production of a soot particle. Our approach is to examine the steps theoretically for reasonableness and to perform experiments to answer questions as they arise. The experiments thus far have concentrated on the nucleation step in laminar premixed flames and have included: molecular beam ion mass spectrometry; Langmuir probes; thermocouple probes; and observation of the effect of molecular structure and flame temperature on the threshold soot index, TSI, and on the total quantity of soot formed.

Since the last meeting, theories relating to the individual steps, Fig. 1, have been organized in order to make quantitative calculations in sooting flames; typical calculations have been performed. There are two motives for this: first, to determine whether the large hydrocarbon ions observed in sooting flames might be a result rather than a cause of the soot formation. Thus far we have found no plausible basis for concluding that the large ions are derived from the soot while, on the other hand, there are many reasons for believing that the large ions are a direct path to the formation of incipient soot particles. The second motive is to develop the necessary background to construct a computer model for soot formation--agreement of such a model with experiments will be the real test of the ionic (or any other) hypothesis. Application of the theoretical calculations for the individual steps which might be important is demonstrated in Fig. 2, where the characteristic times for processes occurring in a flame seeded with potassium (note P stands for soot particle) are displayed. This particular flame was a premixed ethylene-air flame at atmospheric pressure studied by Haynes, Jander, and Wagner.[1] Some species concentrations had to be estimated to complete this set of calculations. The characteristic times in Fig. 2 are for a position in the flame 2.2 cm above the burner where the average particle diameter is 13 nm. This type of analysis represents a first step in quantitatively understanding the many detailed steps leading to soot formation and can be used as a tool for understanding the relative importance of competing steps, which of course may change with changing flame conditions.

Another problem which has been attacked with vigor since the last meeting is the determination of the absolute total ion and charged species concentrations using Langmuir probes. Such probes are routinely used in nonsooting flames but apparently no one has considered the complications of using them in the presence of charged particles. We have now done this and have measured total ion concentration profiles in acetylene-oxygen flames at 2.67 kPa (20 Torr). The maximum total ion concentrations, as a function of equivalence ratio, are presented in Fig. 3. An increase in total ions beyond the critical equivalence ratio for soot formation has been observed previously (e.g., Delfau et al.).[2] The significance of the measurements reported in Fig. 3 is that the minimum in the "maximum ion concentration" occurs in flames well beyond the threshold equivalence ratio for soot formation. Our hypothesis, which will be further evaluated when particle size vs. equivalence ratio measurements are available for this flame, is that in such rich flames the particle diameters and concentrations are sufficient to produce thermal ionization of particles.[3]

The effect of measured flame temperature (by radiation corrected thermocouples) on TSI and soot yield is being determined in premixed laboratory flames at 1 atm. The flame temperature is varied by the addition of N_2 or O_2 to air. Fuels studied to date include acetylene, ethylene, propane, heptane, benzene, toluene, and decalin. Total ion concentrations in these flames will be determined by Langmuir probes.

The ionic mechanism of soot formation (chemi-ionization followed by ion-molecule growth reactions) in flames continues to be supported by both experiment and theory.

REFERENCES

1. Haynes, B.S., Jander, H., and Wagner, H.Gg., Seventeenth Symposium (International) on Combustion (The Combustion Institute, Pittsburgh, 1975) p. 1461.

2. Delfau, J.L., Michaud, P., and Barassin, A., Combust. Sci. Techn. 20, 165 (1979).

3. Calcote, H.F., Combust. Flame 42, 215 (1981).

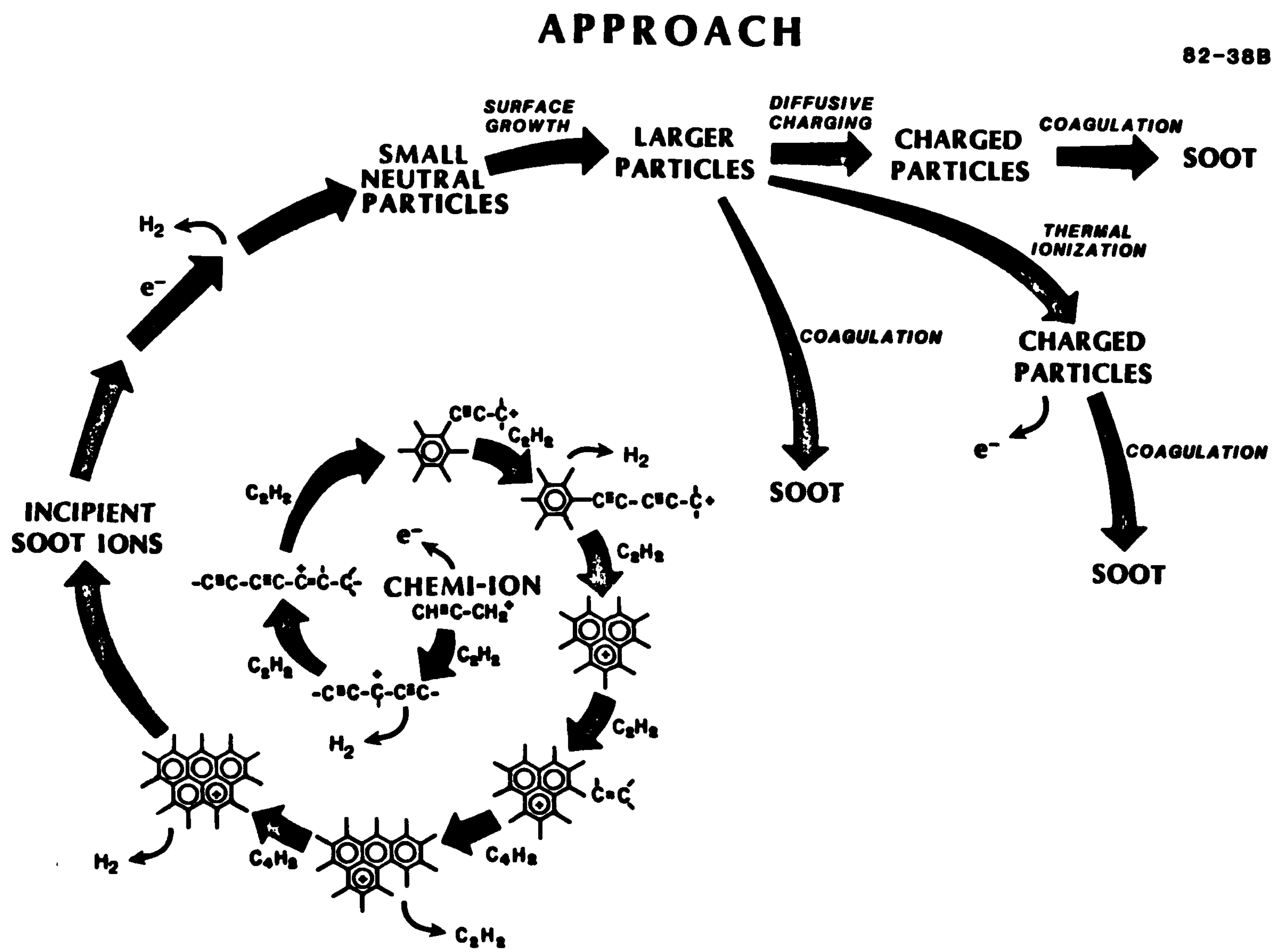


FIGURE 1 HYPOTHESIS BEING TESTED BOTH EXPERIMENTALLY AND THEORETICALLY

ACCOMPLISHMENTS

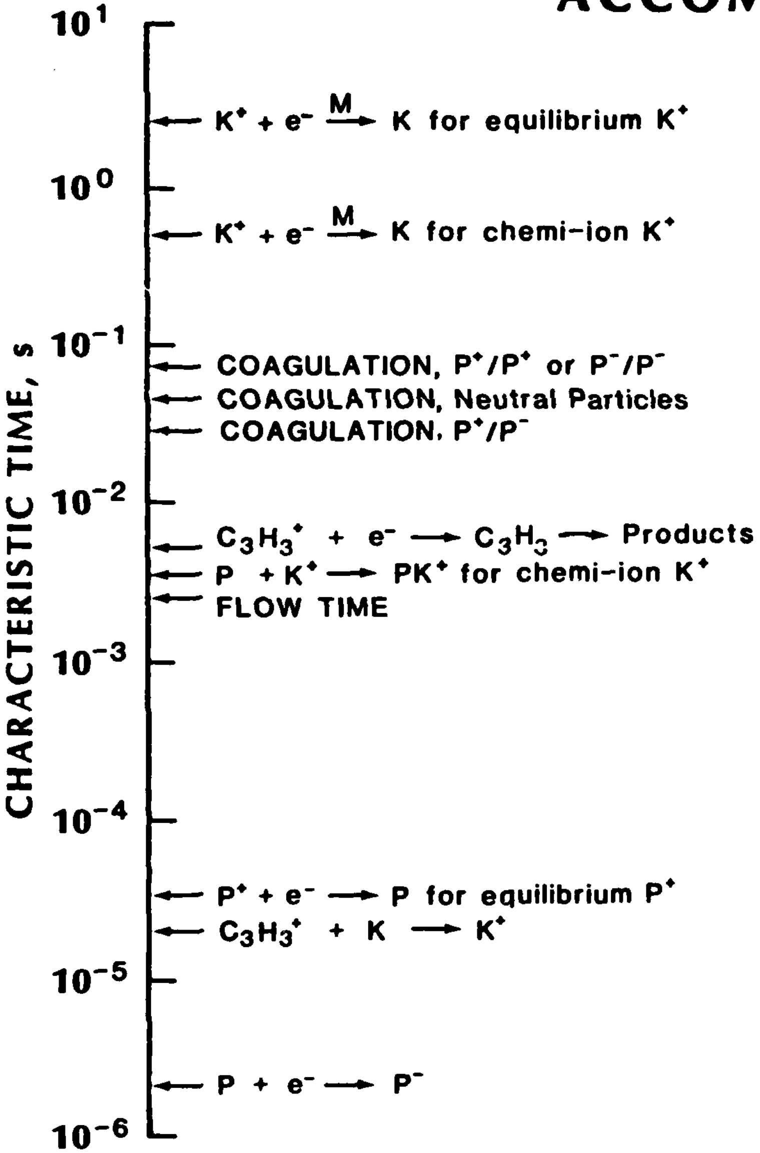


FIGURE 2 CHARACTERISTIC TIMES FOR SOME OF THE IMPORTANT STEPS IN SOOT FORMATION IN A PREMIXED ETHYLENE-AIR FLAME

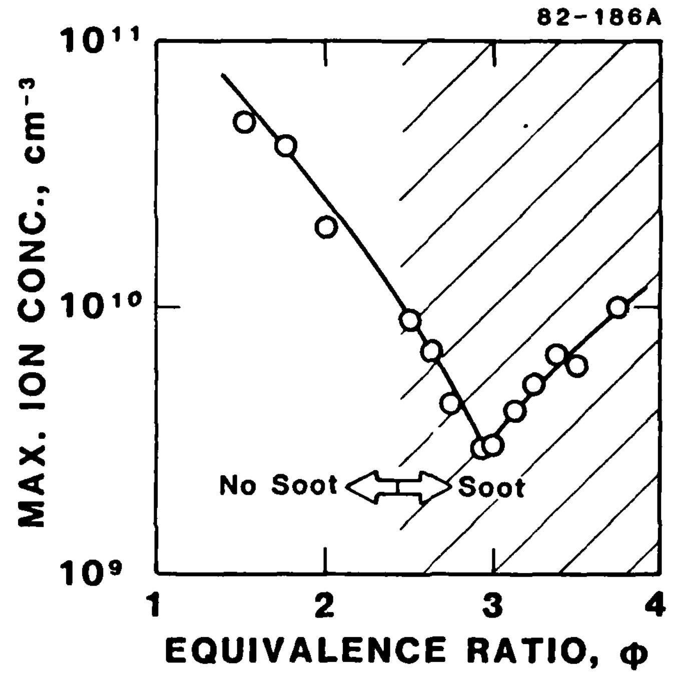


FIGURE 3 ABSOLUTE MAXIMUM ION CONCENTRATION IN A PREMIXED ACETYLENE-OXYGEN FLAME

TURBULENT MIXING AND COMBUSTION OF MULTI-PHASE REACTING FLOWS IN RAMJET AND DUCTED ROCKET ENVIRONMENTS

by

K. C. Schadow and M. J. Lee
Naval Weapons Center
China Lake, California

1 October 1982

Distribution limited to U.S. Government agencies only; test and evaluation; 1 October 1982. Other requests for this document must be referred to the Naval Weapons Center.

TURBULENT MIXING AND COMBUSTION OF MULTI-PHASE REACTING FLOWS IN RAMJET AND DUCTED ROCKET ENVIRONMENTS

K. C. Schadow and M. J. Lee
Naval Weapons Center
China Lake, California

Turbulent mixing and combustion of multi-phase flows are relevant to problems in many airbreathing propulsion systems, such as the gas generator ramjet (ducted rocket) with solid boron propellants and the slurry fuel ramjet. The ability to deal with the complex flow field in these systems requires detailed experimental and analytical knowledge of a number of coupled physical and chemical processes, including turbulent mixing, recirculating flow, and gaseous/particulate fuel ignition/combustion.

In recent years, considerable progress has been made towards development of analytical models to deal with the multitude of couple mechanisms, however, evaluation of the models has been hampered by the lack of detailed experimental flow-field information. The objective of this program is to obtain such experimental data that would specifically aid evaluation and further refinement of analytical techniques developed by Sciences Applications Inc. (Edelman and Harsha) under AFOSR funding.

Because of the complexity of the phenomena to be studied, a systematic step-by-step approach will be taken for both the fuel characteristics (gaseous fuels, boron-laden gaseous fuels, liquid fuels, and slurry fuels) and the flow field (axisymmetric-coaxial, axisymmetric with dump, axisymmetric-noncoaxial, and three-dimensional) (Fig. 1).

Experiments with gaseous fuels in an axisymmetric, coaxial flow field were completed. Radial and axial profiles of pressure, velocity, species concentration and temperature were determined.

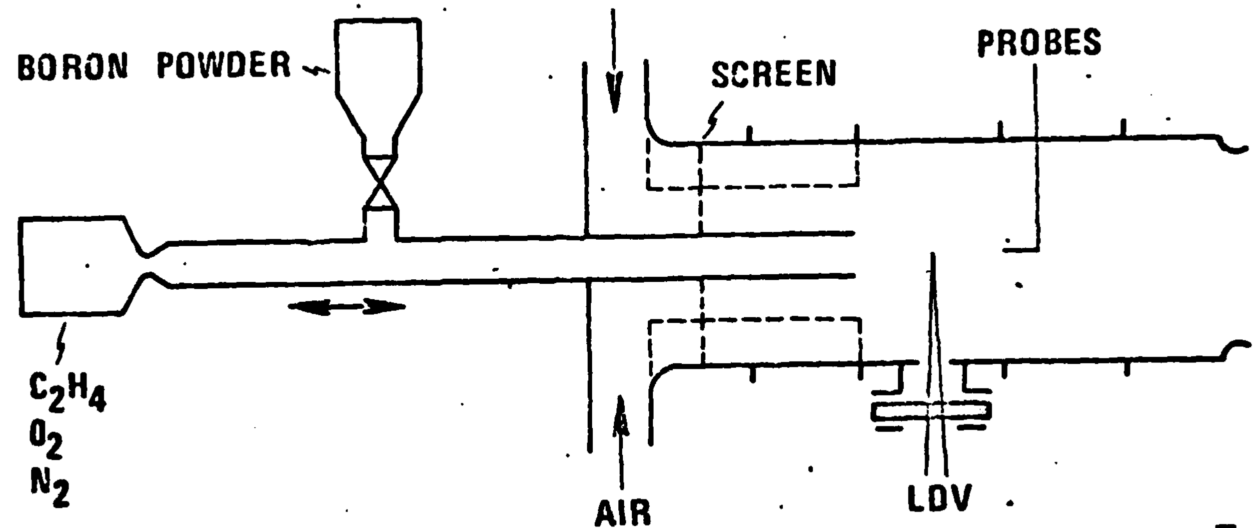
A major impetus of the work with gaseous fuels has been the establishment of a baseline case for both the experimental work and the analytical model developments. From the experimental standpoint, the gas-phase mixing tests provide a set of data for comparison with those obtained in more complex, particle-laden flows in the same apparatus. This basic comparison aspect applies also to the analytical model development, but in this case the comparison of the analytical results with the experimental data provides an indication of required model improvements as well. Although the overall agreement between the analytical results and the experimental data shown in Fig. 2 is reasonably good, it is evident that the model indicates near-stoichiometric combustion temperatures in the near field ($x/D = 0$), which was not experimentally observed. Further, the data indicate the presence of oxygen along the flow centerline at the nozzle exit (Fig. 2). The presence of oxygen in this region is not indicated by analytical model results, because the model utilizes an equilibrium gas-generator nozzle exit assumption to provide initial conditions for the computations, and/or does not consider turbulence-chemistry interactions. The latter involve the modification of basic chemical reaction rates by the fluctuations in temperatures and species mass fraction in a turbulent flow, along with intermittency phenomena.

Prior to the detailed flow measurements, a large number of preliminary tests had to be performed to select baseline operational conditions. Auto-ignition of the hot, gas generator reaction products in the airstream was difficult to achieve under simple flow conditions (no recirculating flow), yet realistic operational ramjet conditions (low gas-generator combustion temperature and low ramjet combustor pressure). The requirement to maintain a simple flow field was crucial to make a meaningful experiment/theory comparison possible.

Tests were started with boron particle-laden, gaseous fuels. In these tests, the boron particles were injected into the gas generator from a powder container with nitrogen as carrier gas. Strong pressure oscillations in the ramjet combustor were experienced. These oscillations at about 50 Hz originated in the boron particle feed system and resulted in oscillating boron particle mass flow. The oscillations, which were identified as the Helmholtz mode of the particle container, were minimized by a suppression device. However, the remaining small particle mass flow fluctuations still provided problems at low ramjet pressure (18 psia) and low gas generator combustion temperature (1350K) in that they caused a highly irratic flame in the ramjet combustor. The pressure (temperature) had to be increased to 24 psia (1650K) to achieve acceptable flame stability. At these conditions, radial and axial temperature profiles were determined.

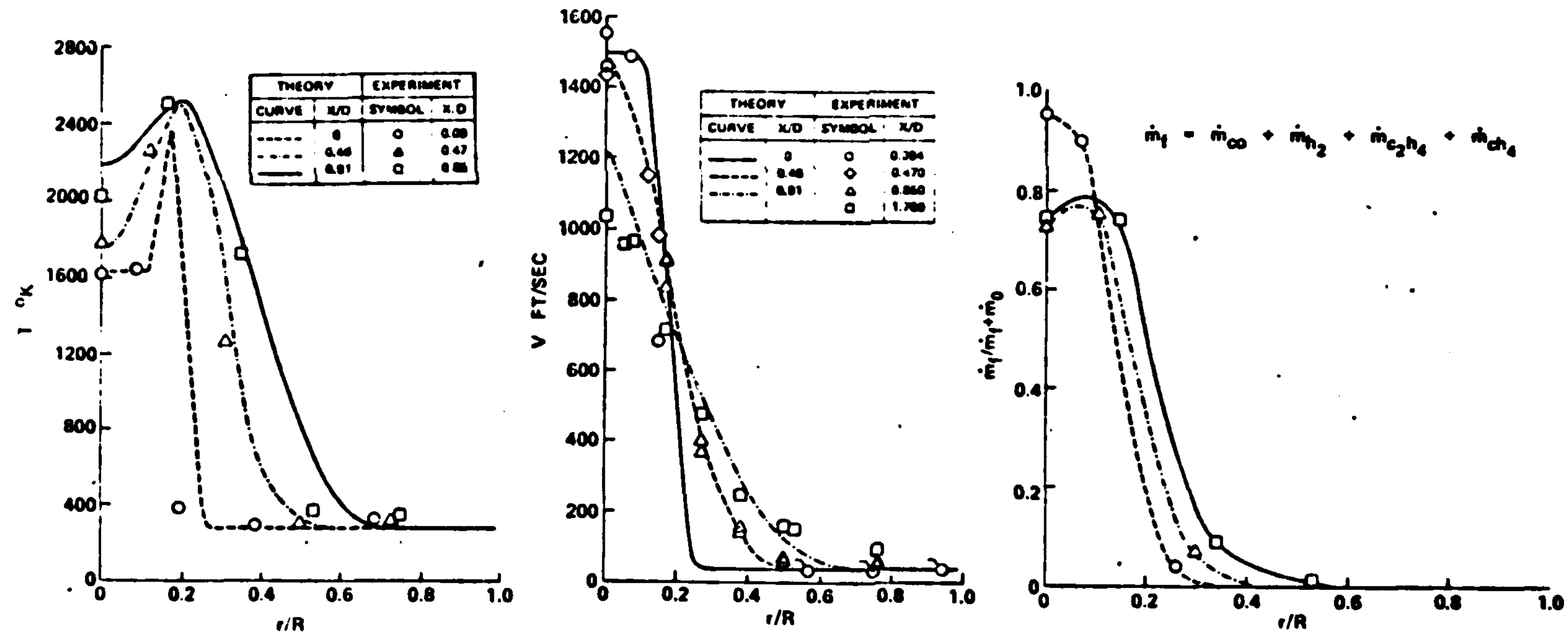
TURBULENT MIXING AND COMBUSTION OF MULTIPHASE FLOWS

- APPROACH
  - AXISYMMETRIC, 5-INCH DIAMETER LABORATORY COMBUSTOR TESTS WILL BE PERFORMED.
  - FUEL CHARACTERISTICS WILL BE VARIED FROM GASEOUS FUELS (BASELINE) TO BORON PARTICLE-LADEN GASEOUS FUELS, LIQUID FUELS AND SLURRY FUELS.
  - FLOW FIELD CHARACTERISTICS WILL BE VARIED FROM COAXIAL MIXING TO COAXIAL MIXING WITH DUMP AND NON-COAXIAL MIXING WITH CIRCUMFERENTIAL SLOT (AXISYMMETRIC) AND WITH AIR MULTI-INLETS (3 DIMENSIONAL).
  - MEASUREMENTS WILL BE MADE WITH INTRUSIVE PROBES AND NON-INTERFERENCE OPTICAL DIAGNOSTIC TECHNIQUES.



TURBULENT MIXING AND COMBUSTION OF MULTI-PHASE FLOWS

- ACCOMPLISHMENTS
  - FUEL-RICH PLUME IGNITION REQUIREMENTS ESTABLISHED FOR GASEOUS FUELS IN TESTS WITH VARYING PRESSURE, TEMPERATURE, FUEL INJECTION VELOCITY AND FUEL INJECTOR GEOMETRY.
  - AXIAL AND RADIAL PROFILES (SPECIES, TEMP, VELOCITY) DETERMINED FOR GASEOUS FUELS FOR ESTABLISHING BASE LINE CONDITIONS FOR BORON COMBUSTION EXPERIMENTS.
  - EXPERIMENTAL DATA COMPARED WITH MODEL PREDICTIONS BY SAI.



- OVERALL AGREEMENT BETWEEN EXPERIMENT AND ANALYTICAL PREDICTIONS REASONABLY
- AREAS FOR MODEL IMPROVEMENT IDENTIFIED
- BORON PARTICLE-LADEN PLUME IGNITION REQUIREMENTS ESTABLISHED. AXIAL AND RADIAL TEMPERATURE PROFILES DETERMINED.

HIGH DENSITY FUEL IGNITION AND COMBUSTION IN RAMJET AND DUCTED ROCKET ENVIRONMENTS

Merrill K. King, James Komar, Ronald Fry

Atlantic Research Corporation
Alexandria, Virginia

Boron is a particularly attractive ingredient for airbreathing missile fuels due to its high density and heating value. For achievement of the full potential available from this material, boron particles must ignite and burn completely within extremely limited residence times available in typical ramburners. Since boron particles are generally coated initially with an oxide layer which inhibits combustion and must be removed before "full-fledged" combustion can begin, considerable time may be consumed during this "ignition" stage. In addition, boron has a very high boiling point, necessitating relatively slow surface burning even after the oxide has been removed. As a result, afterburning efficiency problems have been encountered with boron fuels, particularly at low ramburner pressures associated with high altitude operation. Thus, fuel tailoring and ramburner combustor design optimization are particularly critical for boron-containing fuels - definition of proper approaches to such optimization depends on thorough understanding of the phenomena involved in boron particle and boron agglomerate ignition and combustion.

In this program, a multi-faceted experimental and theoretical effort aimed at developing this understanding and identifying means of utilizing the full potential of boron fuels is being carried out. Among the studies currently in progress are modeling of single particle boron ignition and combustion in various atmospheres, experimental determination of ignition and combustion times of boron particles of various sizes in various surroundings, definition of kinetics of key processes involved in boron ignition, modeling of fractional conversion of boron clouds of given size distributions in slurry ramjet combustors, and experimental definition of mechanisms involved in the ablation and subsequent combustion of consolidated boron fuel grains in high temperature air crossflow (boron solid fuel ramjet concept). The major emphasis of this presentation will be on the single particle ignition and combustion modeling studies.

A new model of ignition of initially oxide-coated single boron particles in both wet and dry atmospheres has been developed. (Several optional scenarios are considered for wet atmospheres, as depicted in the first figure - the major differences lie in treatment of possible water reaction with boron at the B/B_2O_3 interface. In the first option it is assumed that there is no such reaction while in Option B water is assumed to react with boron at the interface to form B_2O_3 and hydrogen, and in Option C, water is assumed to react with boron <u>and</u> B_2O_3 at the interface to produce boroxine.) In this model, differential equations describing the rate of change of particle temperature, particle velocity, oxide thickness, and particle size are numerically integrated until thermal runaway occurs (subsequent to removal of the oxide coating and melting of the boron) or until it becomes obvious that such runaway will not occur. In the former case, the time at which runaway occurs is defined as the ignition time. Considerable attention is paid to development of rate expressions for various processes occurring during the ignition process. Preliminary comparisons of model predictions with Macek data for single-particle ignition in wet and dry environments are quite encouraging, as shown in the top two panels of the second figure. Exercise of the model for several ambient gas composition versus time profiles suggests a possible staging procedure for minimizing boron particle ignition times in air-augmented rocket combustors (Panel 3 of Figure 2).

In addition, models at several levels of sophistication of clean (no oxide coating) single boron particle combustion in O_2-N_2 atmospheres under diffusion-limited conditions (large particles) have been examined. It is found that all two-stage reaction models (oxidation of boron by B_2O_3 to suboxide(s) at the surface followed by subsequent reaction of the suboxide(s) with O_2 to B_2O_3) examined can be used for burn rate calculation and that in fact a very simplified closed-form expression yields predicted burn rates essentially identical to the most complete model examined. In addition, one of the simplified models as well as the "full-up" model can also be used for calculation of extinguishment conditions (postulated to occur when the partial pressure of B_2O_3 gas adjacent to the surface exceeds the B_2O_3 vapor pressure associated with the calculated surface temperature). Three model variants have been extended to allow for finite-rate kinetic limitations on surface reactions - calculations of burn times with these models indicate, as expected, a shift from d^2-law behavior to d^1-law behavior for small particles. The most complete of the models have been extended to treat B-H-O-N-C systems. It is shown that Macek burn-time data for small particles, obtained in atmospheres containing significant H_2O and CO_2 as well as O_2, can be fit well with the finite surface kinetics model (BCOMBKIN)for reasonable values of required input transport and reaction rate parameters. (See the 4th panel of Figure 2.) Finally, effects of finite-rate gas kinetics in combination with the finite surface kinetics have been briefly examined, with a tentative conclusion that the former will in general have little effect on predicted burning rate.

A preliminary model of a boron slurry ramjet combustor as a well-stirred ignition zone followed by sequential plug-flow zones with staged air addition has been developed and is being used to aid in design of such combustors in terms of patterns of air addition. In this model, the aforementioned single particle boron ignition model (with modifications to allow for cloud effects) has been coupled with mass and enthalpy balances for the various zones and the simplified burning rate expression mentioned above. (Modifications to allow for kinetics limitations for small particles as calculated with the BCOMBKIN code will be added to this analysis shortly.)

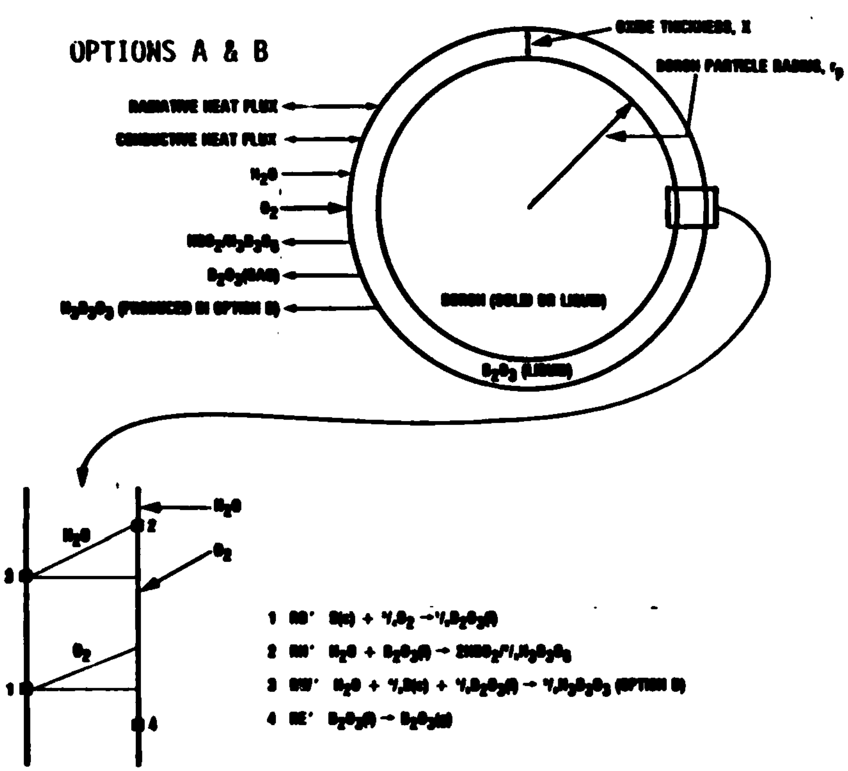
A flat-flame burner facility with sophisticated diagnostics for study of small boron particle ignition and combustion phenomena has been completed and limited data obtained for particles in the 10-40 micron diameter particle size range-analysis of these data are in progress as testing continues. This apparatus will also be used in the near future to study the kinetics of the reacton of B_2O_3 liquid with water gas, to improve the modeling of boron ignition in wet atmospheres.

The mechanisms involved in the ablation of consolidated boron grains in a high temperature air crossflow and in subsequent combustion of material leaving the surface are not well understood. (In fact, even the nature of the products leaving the surface is not well defined.) It is thought that two factors of major importance are radiation heat feedback from particles burning in the mainstream to the surface and the nature of the flow and turbulance profiles near the surface. An apparatus for study of these effects, described in last year's presentation is in the final stages of construction. Diagnostics to be employed in this study include high-speed photography, laser schlieren, LDV and laser raman spectroscopy for definition of the nature of products leaving the surface and processes occurring in the gas phase, while imbedded thermocouples and heat flux gages will be used to determine subsurface temperature profiles and heat feedback fluxes (radiative and non-radiative). Sampling probes may also be employed for definition of ablation products.

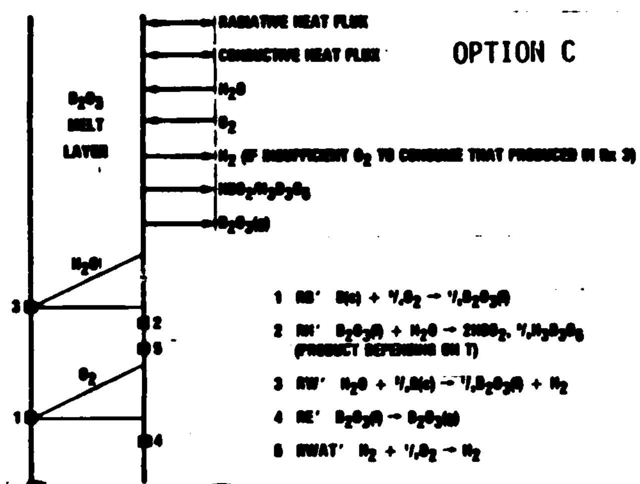
FIGURE 1

IGNITION MODELS EXAMINED

OPTIONS A & B



OPTION C



COMBUSTION MODELS EXAMINED

I. DIFFUSION-LIMITED COMBUSTION, B-O-N SYSTEMS
   A. SINGLE ONE-STAGE REACTION OF BORON TO B_2O_3 GAS AT SURFACE
   B. SURFACE REACTION OF $B_2O_3(g) + B(c) \rightarrow B_2O_2(g)$ AT SURFACE
   C. SURFACE REACTION OF $B_2O_3(g) + B(c) \rightarrow BO(g)$ AT SURFACE
   D. SURFACE REACTION OF $B_2O_3(g) + B(c) \rightarrow BO, B_2O_2$ AT SURFACE
   E. SHIFTING EQUILIBRIUM THROUGHOUT GAS PHASE AND AT SURFACE

II. ALLOWANCE FOR FINITE-RATE SURFACE KINETICS, B-O-N SYSTEMS
   A. SINGLE ONE-STAGE REACTION OF BORON TO B_2O_3 GAS AT SURFACE
   B. KINETICS VARIANT OF ID.
   C. KINETICS VARIANT OF IE.

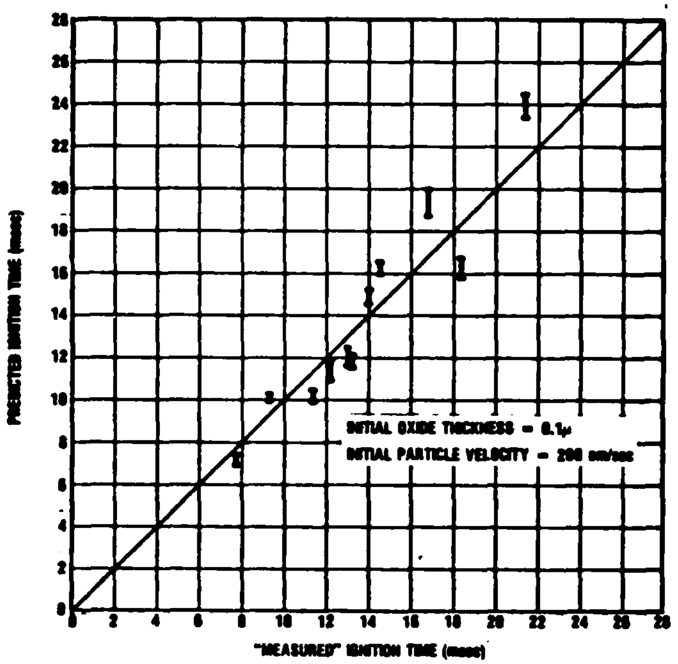
III. DIFFUSION-LIMITED COMBUSTION, B-H-O-N-C SYSTEMS

IV. ALLOWANCE FOR FINITE-RATE SURFACE KINETICS, B-H-O-N-C SYSTEMS (BCOMBKIN CODE)

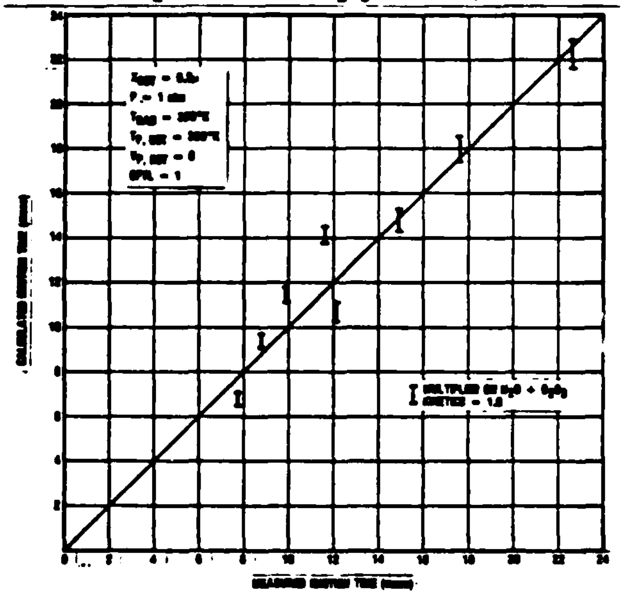
V. EXAMINATION OF FINITE-RATE GAS-PHASE KINETICS EFFECTS.

FIGURE 2

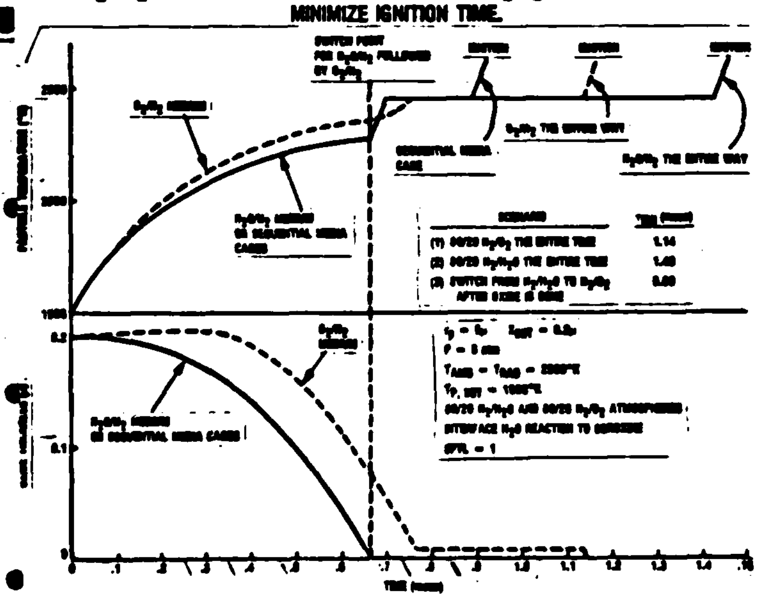
COMPARISON OF MODEL PREDICTIONS AND MACEK DATA FOR BORON PARTICLE IGNITION TIMES IN DRY ATMOSPHERES.



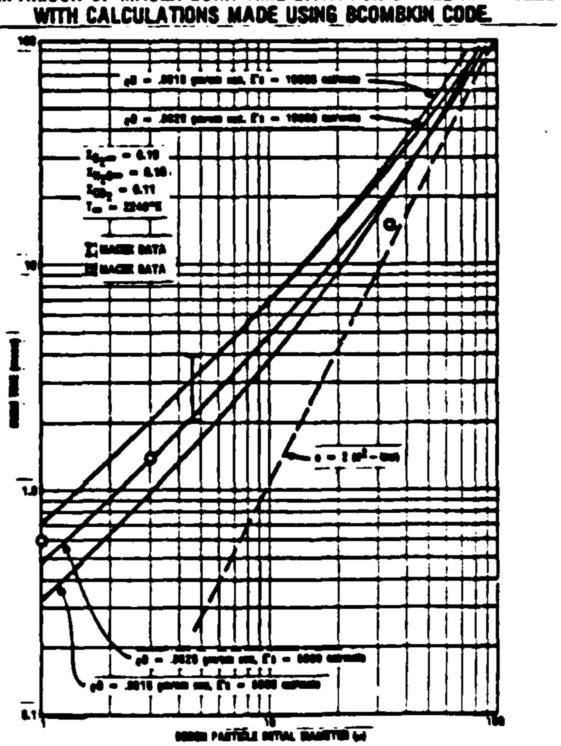
COMPARISON OF MACEK DATA AND MODEL PREDICTIONS FOR BORON PARTICLE IGNITION TIMES IN WET ATMOSPHERES (OPTION B RE H_2O REACTION AT B/B_2O_3 INTERFACE).



EXAMINATION OF POSSIBLE EFFECT OF STAGING THE ENVIRONMENT TO WHICH A BORON PARTICLE IS EXPOSED (FIRST EXPOSING IT TO A HOT H_2O/N_2 ENVIRONMENT, FOLLOWED BY A HOT O_2/N_2 ENVIRONMENT) TO MINIMIZE IGNITION TIME.



COMPARISON OF MACEK BURN TIME DATA FOR SMALL PARTICLES WITH CALCULATIONS MADE USING BCOMBKIN CODE.



BORON SLURRY COMBUSTION IN TURBULENT REACTING FLOWS
ADVANCED FUELS COMBUSTION RESEARCH

(AFOSR Contract No. F49620-82-K-0011)

Irvin Glassman, Frederick L. Dryer and Forman A. Williams

Department of Mechanical and Aerospace Engineering
Princeton University
Princeton, NJ 08544

The purpose of this portion of this research project is to study boron combustion and turbulent combustion as they relate to air-breathing propulsion. An intended focus is the use of boron slurries in combustors. Thermochemical performance calculations demonstrate appreciable advantages associated with addition of boron to fuels. One essential element in the realization of these advantages is the achievement of efficient combustion of the boron. Initial work related to boron slurries therefore has focused on developing proper theoretical descriptions of boron particle ignition and of boron particle combustion. Preparations are in progress for experimental investigations on the burning of individual droplets of boron slurries. The work on turbulent combustion has concerned gas-phase flames, both premixed and nonpremixed, and has been directed toward developing predictive capabilities for the evaluation of turbulent flame speeds and of conditions for turbulent flame stabilization.

The methods employed in the studies related to boron combustion are both theoretical and experimental. In the experimental work single droplets are ignited and burned in various atmospheres. The combustion history is examined by high-speed motion-picture photography. Unburnt residues are recovered and examined microscopically. The theoretical work has addressed both the ignition and the combustion of boron particles, and it is intended to address the burning of slurry droplets, with attention given to mechanisms of transport of solid constituents from the liquid into the gas.

Two new findings concern the ignition and the combustion of boron particles. In the past it has generally been assumed that during the ignition phase oxygen dissolves in a liquid layer of B_2O_3 on the surface of the boron particle and diffuses to the boron surface where it reacts. It has been found that it is much more likely that instead the boron dissolves in the liquid B_2O_3 and migrates toward the surface of the liquid where it reacts with oxygen. Suboxides may well be formed during this migration process. Concerning diffusion-controlled burning in the absence of an oxide layer, it has been shown that for a simplified model originally identified independently by Mohan and Williams and by Glassman and adopted more recently by King, the calculated burning rate varies very little if details of the model are varied. In this model oxygen reacts with gaseous BO or $(BO)_2$ at a flame sheet in the gas and forms gaseous B_2O_3 which diffuses to the liquid boron surface where reaction occurs to produce gaseous BO and $(BO)_2$. The key high-temperature problem was identified as the chemical rate-controlled burning of small particles, and possible chemical mechanisms for this have been considered.

The methods employed in the studies of turbulent combustion are purely theoretical. To avoid questionable modeling hypotheses perturbation methods we used based on formal expansions for large or small values of parameters. In the premixed-flame studies a large parameter is the ratio of a representative turbulence scale to the thickness of a laminar flame. In both the premixed-flame and the diffusion-flame studies another large parameter is the strength of the dependence of the overall rate of heat release on the temperature. Matched asymptotic expansions are then introduced to obtain formulas for premixed turbulent flame speeds and to define conditions for local extinction of turbulent diffusion flames.

A new finding of the work on premixed turbulent flames concerns the influences of the density change associated with the heat release on the flame structure and on the flame dynamics. In the absence of this fluid-dynamical density-change effect, the reaction zone is readily subjected to significant influences from nonadiabaticity or from differing diffusive conductances for heat and reactant species (Lewis numbers different from unity). In the presence of the effect, the expansion associated with the density change lessens gradients locally and thereby greatly reduces the sensitivity of the reaction zone to external perturbations. Conditions for instability of wrinkled flames thereby are modified significantly. Many of the resulting modifications have now been calculated.

A new finding of the work on turbulent diffusion flames concerns the specification of the height of lift-off of the flame at a fuel jet. From asymptotic analysis the conditions for flamelet extinction were related to the local, instantaneous rate of scalar dissipation. By equation conditions for nonexistence of the flame with the condition that the dissipation rate exceed its critical value for extinction, lift-off heights were calculated in terms of mean dissipation rates of turbulent jets. Reasonable agreement with measured lift-off heights was obtained. The viewpoint developed here differs significantly from the viewpoints of earlier work in that premixing of fuel and oxidizer at the molecular level now plays no role in the lift-off prediction, and premixed turbulent flame speeds lose their fundamental relevance to diffusion-flame lift-off.

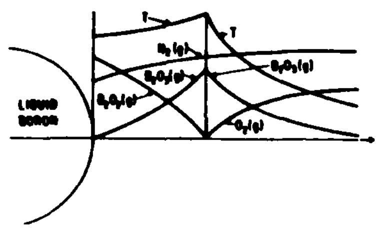
The results reported here are fundamental in character and are intended to provide basic information that can be of use in practical problems of air-breathing propulsion. They contribute to improvements in capabilities for predicting the combustion of boron-containing fuels and turbulent combustion.

STUDIES OF COMBUSTION OF BORON AND OF BORON SLURRIES

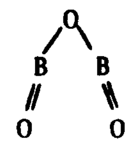
IGNITION: MORE LIKELY THAT B RATHER THAN O_2 DIFFUSED THROUGH $B_2O_3(\ell)$.

COMBUSTION:

MECHANISM



STRUCTURES



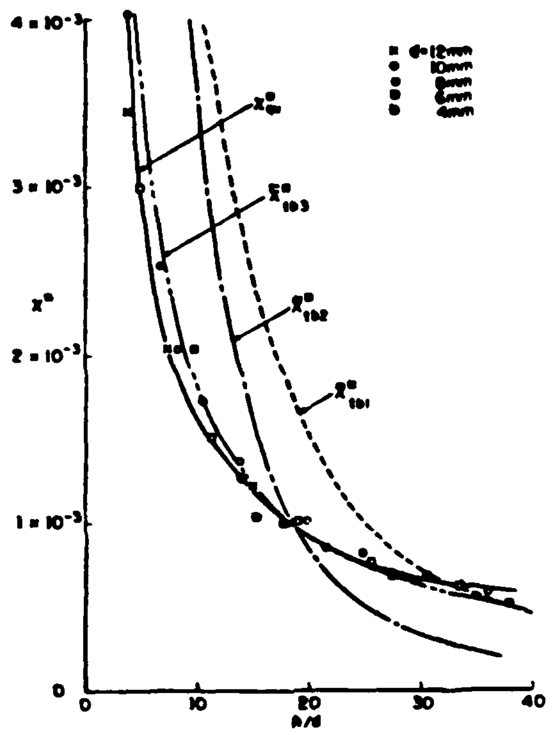
and

O = B - B = O

A POTENTIAL CRITICAL-RATE STEP

$B_2O_3(g) + B(\ell) \rightarrow 3\,BO(g)$

THEORY OF TURBULENT COMBUSTION



LIFT-OFF HEIGHT OF DIFFUSION FLAME DEPENDS ON VALUE OF SCALAR DISSIPATION FOR EXTINCTION

DENSITY DECREASE IN PREMIXED FLAME PROTECTS REACTION ZONE FROM EXTERNAL PERTURBATIONS

Combustion Studies of High Energy-High Density
Fuels and Predictions of Spray Combustion Interactions
(Contract F33615-82-K-2256)

G. M. Faeth, Principal Investigator
Department of Mechanical Engineering
The Pennsylvania State University
University Park, PA 16802

ABSTRACT

Carbon slurries, formed by suspending carbon-black particles in a liquid hydrocarbon carrier (e.g. JP-10), have high volumetric energy densities when used in airbreathing combustion systems. These fuels are attractive since they provide a means of extending the range of volume-limited vehicles. Initial study of the combustion of carbon slurries in gas turbine combustors and well-stirred reactors, however, indicated that carbon slurries required a greater combustor volume for good combustion efficiency than conventional liquid fuels--tending to reduce potential system performance gains. The objective of research in this laboratory is to investigate the combustion properties of carbon slurries in order to help find improved fuel formulations and combustor designs, which minimize residence time requirements, so that the full potential of carbon slurry fuels can be achieved.

The first phase of the investigation involved observations of relatively large drops (400-1000 microns in diameter) supported at various positions in a turbulent diffusion flame of known structure (mean velocities, temperatures, and species concentrations as well as turbulence properties) [1-4].* It was found that carbon slurry drops burned in two stages. During the first stage, which is relatively short, the drop heats-up and the liquid evaporates, leaving a porous agglomerate consisting of all the carbon-black particles originally in the slurry. During the second stage, which is at least an order-of-magnitude longer than the first stage, the carbon agglomerate heats-up and either reacts or is quenched depending upon its position in the flame. These results provided three important findings: (1) the relatively slow reaction of the agglomerates was responsible for the increased residence-time requirements for combustion of carbon slurries; (2) the size of the carbon particles (agglomerates) to be burned was primarily controlled by the original size of the drops in the spray and not by the size of the original carbon-black particles; and (3) rates of agglomerate reaction are strongly influenced by their environment (local fuel equivalence ratio) in the flame which suggested combustor design modifications to increase the time of exposure of agglomerates to optimum environments in order to achieve good combustor efficiencies within a small combustor volume.

A model of the process was also developed [1-4]. The objective of the model was to assist interpretation of measurements and to provide a means of extrapolating the results to combustor conditions--where, unlike the tests,

*Numbers in brackets denote references.

the particles are not subjected to a fixed environment. This model yielded good predictions of particle-life histories (the variation of diameter, liquid content, carbon mass and temperature) for both stages of the process.

The current investigation involves observation of carbon slurry combustion for particle sizes more representative of practical combustors (10-100 microns initial diameter) [5-8]. Experiments are being conducted with freely-moving particles injected into the post-flame region of a laminar flat-flame burner. The particles are formed as a monodisperse stream from a Berglund-Liu aerosol generator. The burner operates with various gas mixtures to achieve a range of fuel equivalence ratios and gas temperatures. Gas temperatures are measured with fine-wire thermocouples corrected for radiation errors. Gas compositions are measured by sampling and analysis with a gas chromatograph. Gas and particle velocities are measured using laser-Doppler anemometry. Agglomerate temperatures are found by optical pyrometry. Agglomerate mass and diameter are obtained by capturing the particles with a quenching probe. These measurements fully characterize the environment and provide the agglomerate temperature, mass and diameter as a function of residence time in the flow.

Initial work with this apparatus involved measurements to study pore development in the carbon agglomerate as reaction proceeds and to evaluate theoretical predictions for practical agglomerate sizes. It was found that pore structure parameters and agglomerate density were primarily a function of extent of reaction and were relatively independent of initial agglomerate size and local flame environment. As a result, the model proved to be effective for predicting agglomerate-life-histories even though it had been developed using results for large particles. This is fortunate since it simplifies application of the present laboratory results to practical combustor operating conditions.

Current work involves application of these experimental and theoretical techniques to investigate effects of fuel formulation. Since carbon agglomerate reaction is the rate-controlling step in the combustion of carbon slurries, we are concentrating on effects of carbon black properties. This includes the effect of carbon-black type (variations of ultimate carbon particle size for monodisperse blacks and effects of blending different monodisperse blacks) and catalyst (since initial work showed that the use of a lead catalyst increased agglomerate combustion rates for fuel-lean flame conditions [1,3]).

The rate of combustion of monodisperse blacks increases slightly as the ultimate carbon-black particle size is reduced, i.e. size reductions from 300 to 70 nm yielded 10-20% reductions in particle residence times required to react fixed fractions of the carbon. Thus far, test results have also been completed for a single blend (containing 50% by mass each of blacks having ultimate carbon particle sizes of 70 and 300 nm). This material exhibited 10-50% greater residence times for reaction than the monodisperse blacks--depending on flame conditions--suggesting that the presence of smaller particles in the blend tends to inhibit the development of pores. Since blends have improved stability and rheological properties, however, the use of a blend may still yield better combustor performance due to improved atomization.

Results thus far have shown that carbon black properties have an appreciable effect on residence times needed for good combustion efficiency. Therefore, tests are continuing for various carbon-black blends and types and concentrations of catalyst, in order to support carbon slurry fuel development efforts.

References

1. G. A. Szekely, Jr. and G. M. Faeth, "Combustion of Carbon Slurry Drops in a Turbulent Diffusion Flame," AIAA Paper No. 81-0322, 1981.

2. G. A. Szekely, Jr. and G. M. Faeth, "Combustion Properties of Carbon Slurry Drops," AIAA J., Vol. 20, No. 3, pp. 422-429, 1982.

3. G. A. Szekely, Jr. and G. M. Faeth, "An Investigation of Slurry Fuel Combustion," AFWAL-TR-80-2125, January 1981.

4. G. A. Szekely, Jr. and G. M. Faeth, "Effect of Envelope Flames on Drop Gasification Rates in Turbulent Diffusion Flames," Combustion and Flame, in press.

5. G. A. Szekely, Jr. and G. M. Faeth, "Combustion of Carbon Slurry Agglomerates," Proceedings of Fourteenth Fall Technical Meeting, Eastern Section of the Combustion Institute, Pittsburgh, pp. 179-182, October 1981.

6. G. A. Szekely, Jr. and G. M. Faeth, "Reaction of Carbon Black Slurry Agglomerates in Combustion Gases," Nineteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, in press.

7. G. A. Szekely, Jr. and G. M. Faeth, "Effects of Carbon-Black Properties on Combustion of Carbon-Black Slurry Agglomerates," submitted to Combustion and Flame.

8. G. A. Szekely, Jr. and G. M. Faeth, "Combustion of Agglomerates Formed by Carbon Slurry Fuels," AFWAL-82-2085, in press.

AN OVERVIEW OF HIGH-SPEED PROPULSION RESEARCH
NASA LANGLEY RESEARCH CENTER

by

G. Burton Northam*

The objective of the NASA-Langley high-speed aircraft program is to develop the technology base necessary for operation of civil and military systems in the Mach 3 to 10 flight regime. The overall program covers the basic research areas of propulsion, aerodynamics, and structures, and a large data base has been developed in each discipline. The major effort of the aerodynamics activity is in the definition vehicle configurations and nozzle characteristics when the propulsion system is integrated with the vehicle. The structures activity has been concerned with the design of a regeneratively cooled (H_2) long thermal-cycle-life engine structure; it is currently focused on the design, construction, and testing of a hydrogen-cooled engine strut that would demonstrate the needed fabrication techniques and cooling concepts.

The propulsion portion of the Langley program will be highlighted herein. Supersonic combustion ramjet research has been underway at LaRC since 1964 with an emphasis on airframe-integrated scramjets since 1968. The present Langley scramjet concept employs a number of engine modules mounted on the underside of the aircraft. This allows the engine to take advantage of the vehicle bow shock for inlet precompression and uses the aft body of the vehicle for the nozzle expansion. Proper attention to propulsion system/vehicle integration also produces lower external drag. The engine modules each have fixed-geometry inlets with instream struts to complete the compression process. These struts provide a location for instream fuel injection which improves fuel mixing and minimizes combustor length and engine weight. Cold flow wind tunnel tests and simulated flight tests with hot flows, both Mach 4 and Mach 7, have demonstrated the fixed-geometry, airframe-integrated inlet performance. The concept is self-starting and has high pressure recovery and good capture characteristics over this flight Mach number range.

Two research scale engine modules, 8-inches high by 6.4-inches wide using the 3-strut inlet configuration have been constructed and tested at Mach 4 and 7. Test results indicate good performance at Mach 7 simulated flight conditions when Silane SiH_4 (pyrophoric) is used to aid flameholding. At Mach 4 test conditions, the engine experienced a combustor-inlet interactiion when the equivalence ratio was increased beyond the value for which thermal choking was predicted. The tests therefore quantified the supersonic combustion limits and established the requirements for dual-mode combustor operation. Several inlet geometries involving one and two struts with varying amounts of sweep are currently being investigated to reduce inlet-combustor coupling.

*Aerospace Engineer, Hypersonic Propulsion Branch, High-Speed Aerodynamics Division, NASA Langley Research Center, Hampton, VA

Experiments using direct-connect test techniques with single strut hardware simulating the flow about a fuel injector strut were conducted. The results indicate that with some slight modifications, the fixed-geometry scramjet concept should be able to operate with dual-mode combustion. Depending somewhat on the flight Mach number simulated by the test stream (i.e., total temperature), the combustion mode can be shifted from subsonic to supersonic by simultaneously shifting the fuel injection from mostly parallel to mostly perpendicular to the local stream. This mode of operation of the 8-inch engine module was recently demonstrated at GASL. The key is to simultaneously control the mixing, ignition, and flameholding characteristics of the combustor. Flameholding tests using single-strut, direct-connect test hardware are being conducted to determine the effect of scale, total temperature, and equivalence ratio on the blow-off limit of the fuel injector struts.

In 1982, a program was formulated to begin the extension of the fixed-geometry, hydrogen-fueled engine technology to hydrocarbon-fueled concepts. A propane kinetic mechanism has been formulated to predict the reaction time under scramjet conditions for a "typical" hyrocarbon. The model was tested against the ignition data set reported by Burcat, 1971. The effects of pilot fuels and the kintics of piloting are being investigated using modeling and shock tube techniques. A study was also started to obtain heat transfer data required to design a hyrocarbon fuel external prevaporizor. Successful demonstration of external prevaporization would improve combustion efficiency and maintain short combustor length with the hydrocarbon fuel by eliminating the injectiion of liquid fuel into the high velocity main engine flow - injection would be gas phase.

In order to have a capability for future scramjet testing of hydrogen and hydrocarbon scramjets, efforts have begun to prepare the Langley 8-Foot Thermal Structures Tunnel for ramjet/scramjet testing at simulated M4 to M7 flight conditions. The modifications require the design and construction of variable Mach number hardware and a system for oxygen replenishment for the heater. When completed, the facility will be used to test the effects of forebody compression, nozzle expansion, angle of attack, and yaw, and structural performance of the engine. The system could also be used to test ramjet missile performance with systems up to 14 feet in length.

Related to more fundamental research activities, two- and three-dimensional computational fluid dynamic (CFD) codes are being developed to analyze and model inlet and combustor performance. This activity is augmented with numerous contracted programs to develop and evaluate turbulence models, develop and improve 3-D computational techniques, study the influence of temperature and composition fluctuations on combustion kinetics and develop global combustion models that can be used to reduce computational time. In addition, a combustion diagnostics activity is continuing to develop nonintrusive measurement techniques for application in the test facilities mentioned. A Coherent Anti-Stokes Raman Spectroscopy (CARS) system is being developed for measurements in supersonic flames. The results will be used to verify CFD codes that are/have been developed and to assess the limits of validity of the turbulent chemistry models in supersonic reacting diffusion-limited flows.

Finally, Langley also has a program objective to identify critical propulsion technology areas that are necessary to apply the integrated ramjet/scramjet technology to the Navy's Wide Area Fleet Defense mission and to the Air Force Transatmospheric vehicle mission.

Salient results from the various experimental and analytical research programs will be presented, and implications for future research and possible applications will be discussed.

COMBUSTOR/INLET INTERACTIONS AND MODELING OF DUAL-COMBUSTION RAMJET ENGINES

Paul J. Waltrup and Joseph A. Schetz (Consultant)

The Johns Hopkins University Applied Physics Laboratory
Laurel, Maryland 20707

The purpose of this research is to develop a basic knowledge and understanding of the overall engine cycle, individual component flowfields and engine thermochemistry in hypersonic dual-combustion ramjet engines (Figure 1). This basic understanding comes from accurate and analytical models of the engine and its components plus concomitant experiments.

The approach taken here is two-fold. The first is experimental and limited to the combustion induced, shock-separated region between the air inlet and the entrance of the supersonic combustor (Figure 1). Initially, this effort will experimentally characterize the flowfield in this region over a wide range of test conditions and provide the details needed to better understand the complex shock/boundary layer interactions which occur. These data will then be used to develop a semi-empirical model for predicting the length of air duct needed between the inlet and supersonic combustor to prevent these combustion induced disturbances from degrading the inlet's and, therefore, overall engine's performance. The second approach is an analytical effort in which multiple, modular models of the dual-combustion process as well as an overall engine cycle model are being developed and compared with the limited available experimental data. The former will enhance the understanding of the details of the combustion process, such as flow profiles, wall skin friction, wall heat transfer and chemical kinetics, while the latter will provide fundamental global predictive techniques for the overall engine and parametric variations thereof.

Fabrication, installation and instrumentation of the combustor/inlet interaction experimental hardware is complete and initial testing at a combustor inlet Mach number of 2.5 has begun. Examples of measured wall static pressure distributions corresponding to varying degrees of compression (simulating combustion) are shown in Figure 2. Currently, variations in the mass flow split between the inner and outer streams, gas generator exit Mach number, cylindrical duct length downstream of the gas generator exit and Reynold's number are being made to document their affects on the shock interaction region. When sufficient variations have been documented, a semi-empirical model describing this region will be initiated. Future plans include testing at combustor inlet Mach numbers of 1.75 and 3.25 to include their effects on the semi-empirical modeling.

Initial modular models simulating the coaxial mixing and combustion process in the supersonic combustor of a dual-combustion ramjet engine, along with a preliminary analysis for predicting the skin friction and heat transfer losses along the combustor walls, have been developed. The effects of changing thermochemistry are included in both and the coaxial mixing and combustion model features detailed treatments of all the relevant physical processes including: the corner expansion and lip shock, the constant pressure mixing layer, the viscous throat, and the recompression and reattachment regions. The results to date are encouraging in that they are able to predict the length of the combustion flame zone and provide radial and axial flow profiles within the combustor (Figure 3). Axial and radial profiles are not only important for determining the details of the supersonic combustion process, but also in the design of the supersonic exit nozzle where maximum stream thrust efficiency is essential for high overall engine performance. In addition, predicted values of wall skin friction and heat transfer show that both increase with increasing combustor heat release (Figure 3), something heretofor not predicted but observed in past experiments on supersonic combustion ramjet engine combustors. Additional refinements to these analyses, including an improved treatment of the base flow region between the outer and inner annulii and more detailed thermochemistry and transport properties, are currently being incorporated.

COMBUSTOR/INLET INTERACTIONS AND MODELING OF DUAL-COMBUSTION RAMJET ENGINES

Paul J. Waltrup and Joseph A. Schetz (Consultant)

The Johns Hopkins University Applied Physics Laboratory
Laurel, Maryland 20707

The purpose of this research is to develop a basic knowledge and understanding of the overall engine cycle, individual component flowfields and engine thermochemistry in hypersonic dual-combustion ramjet engines (Figure 1). This basic understanding comes from accurate and analytical models of the engine and its components plus concomitant experiments.

The approach taken here is two-fold. The first is experimental and limited to the combustion induced, shock-separated region between the air inlet and the entrance of the supersonic combustor (Figure 1). Initially, this effort will experimentally characterize the flowfield in this region over a wide range of test conditions and provide the details needed to better understand the complex shock/boundary layer interactions which occur. These data will then be used to develop a semi-empirical model for predicting the length of air duct needed between the inlet and supersonic combustor to prevent these combustion induced disturbances from degrading the inlet's and, therefore, overall engine's performance. The second approach is an analytical effort in which multiple, modular models of the dual-combustion process as well as an overall engine cycle model are being developed and compared with the limited available experimental data. The former will enhance the understanding of the details of the combustion process, such as flow profiles, wall skin friction, wall heat transfer and chemical kinetics, while the latter will provide fundamental global predictive techniques for the overall engine and parametric variations thereof.

Fabrication, installation and instrumentation of the combustor/inlet interaction experimental hardware is complete and initial testing at a combustor inlet Mach number of 2.5 has begun. Examples of measured wall static pressure distributions corresponding to varying degrees of compression (simulating combustion) are shown in Figure 2. Currently, variations in the mass flow split between the inner and outer streams, gas generator exit Mach number, cylindrical duct length downstream of the gas generator exit and Reynold's number are being made to document their affects on the shock interaction region. When sufficient variations have been documented, a semi-empirical model describing this region will be initiated. Future plans include testing at combustor inlet Mach numbers of 1.75 and 3.25 to include their effects on the semi-empirical modeling.

Initial modular models simulating the coaxial mixing and combustion process in the supersonic combustor of a dual-combustion ramjet engine, along with a preliminary analysis for predicting the skin friction and heat transfer losses along the combustor walls, have been developed. The effects of changing thermochemistry are included in both and the coaxial mixing and combustion model features detailed treatments of all the relevant physical processes including: the corner expansion and lip shock, the constant pressure mixing layer, the viscous throat, and the recompression and reattachment regions. The results to date are encouraging in that they are able to predict the length of the combustion flame zone and provide radial and axial flow profiles within the combustor (Figure 3). Axial and radial profiles are not only important for determining the details of the supersonic combustion process, but also in the design of the supersonic exit nozzle where maximum stream thrust efficiency is essential for high overall engine performance. In addition, predicted values of wall skin friction and heat transfer show that both increase with increasing combustor heat release (Figure 3), something heretofor not predicted but observed in past experiments on supersonic combustion ramjet engine combustors. Additional refinements to these analyses, including an improved treatment of the base flow region between the outer and inner annulii and more detailed thermochemistry and transport properties, are currently being incorporated.

COMBUSTOR/INLET INTERACTIONS AND MODELING OF HYPERSONIC DUAL COMBUSTION RAMJET ENGINES

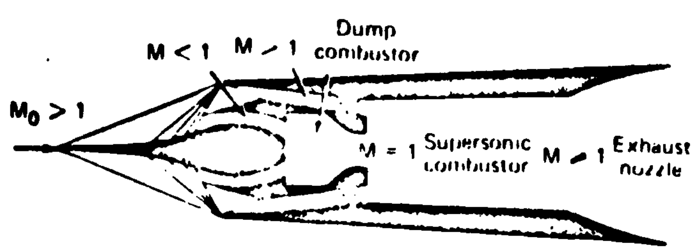
APPROACH

PROBLEMS

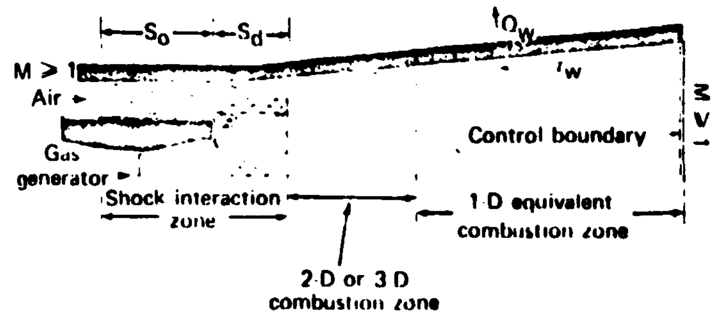
- PREVENT INTERACTION OF COMBUSTION INDUCED SHOCK SYSTEM WITH AIR INLET. UNDERSTAND COMPLEX FLOW STRUCTURE
- DETERMINE LENGTH OF SUPERSONIC COMBUSTOR NEEDED TO COMPLETE FUEL COMBUSTION AND COMBUSTOR WALL SKIN FRICTION AND HEAT TRANSFER LOSSES
- ACCURATELY PREDICT COMPONENT AND OVERALL ENGINE PERFORMANCE

SOLUTIONS

- EXPERIMENTALLY DETERMINE EXTENT OF SHOCK INTERACTION ZONE. DEVELOP SEMI-EMPIRICAL MODEL OF INTERACTION ZONE USING EXPERIMENTAL DATA
- DEVELOP AXIAL MIXING AND COMBUSTION MODEL OF SUPERSONIC COMBUSTOR AND CONCOMITANT BOUNDARY LAYER ANALYSIS
- DEVELOP OTHER COMPONENT AND ENGINE CYCLE ANALYSES. USE AVAILABLE EXPERIMENTAL DATA FOR VERIFICATION



SCHEMATIC OF DUAL COMBUSTION RAMJET ENGINE

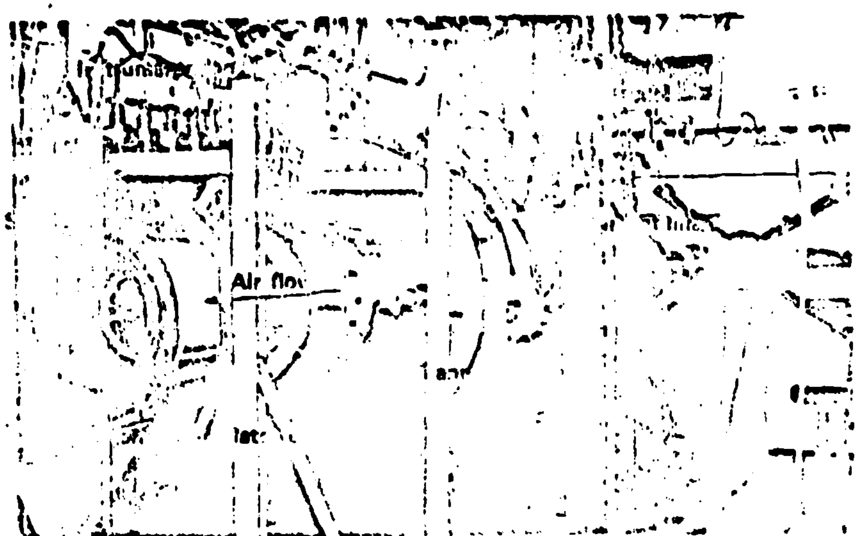


THEORETICAL MODEL FOR DCR COMBUSTION ANALYSIS

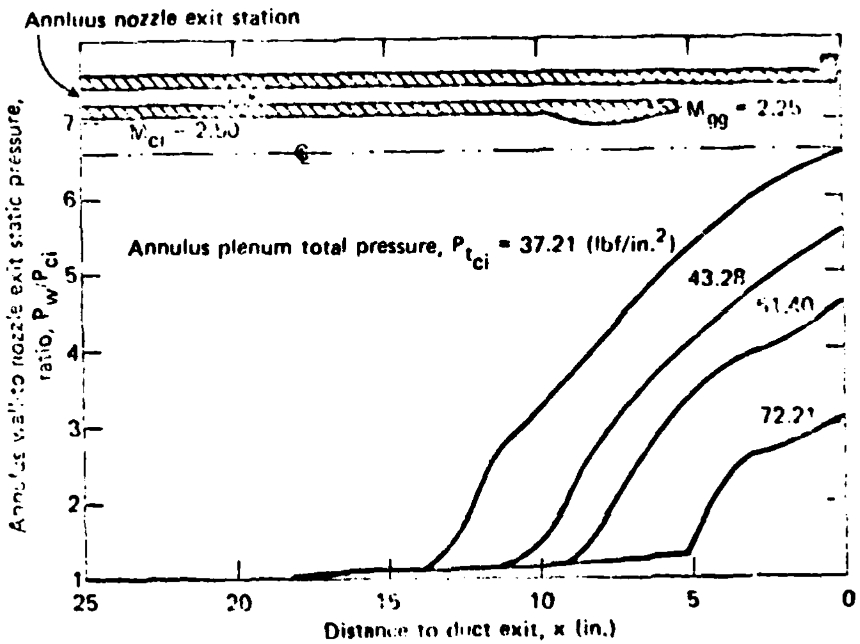
COMBUSTOR/INLET INTERACTIONS AND MODELING OF HYPERSONIC DUAL COMBUSTION RAMJET ENGINES

ACCOMPLISHMENTS
(COMBUSTOR/INLET INTERACTIONS)

- EXPERIMENTAL SETUP COMPLETE
- TESTING WITH MACH 2.5 INLET FLOW INITIATED
- WALL PRESSURES DETERMINE EXTENT OF SHOCK INTERACTION ZONE
- INSTREAM PROFILE AND WALL SHEAR AND HEAT TRANSFER MEASUREMENTS DETERMINE DETAILS OF FLOW STRUCTURE



COMBUSTOR/INLET INTERACTION TEST SETUP



ANNULUS OUTER WALL STATIC PRESSURE DISTRIBUTIONS

COMBUSTOR/INLET INTERACTIONS AND MODELING OF HYPERSONIC DUAL COMBUSTION RAMJET ENGINES

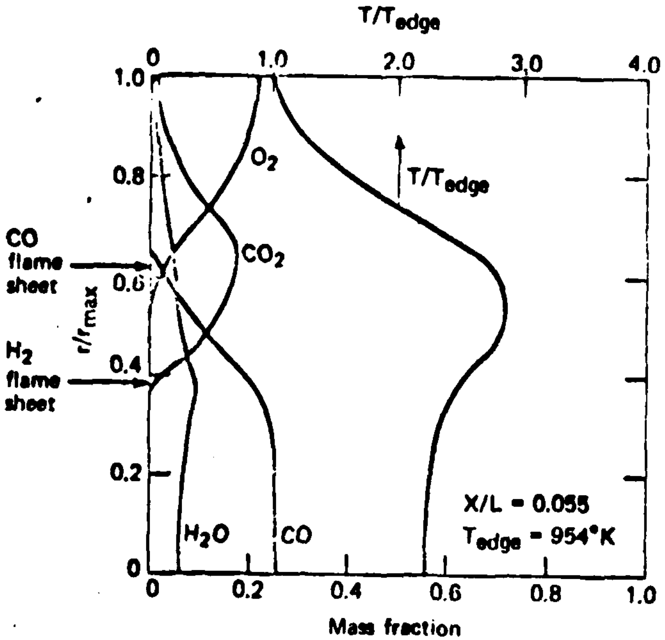
ACCOMPLISHMENTS
(COMBUSTOR MODELING)

COAXIAL COMBUSTOR MODEL

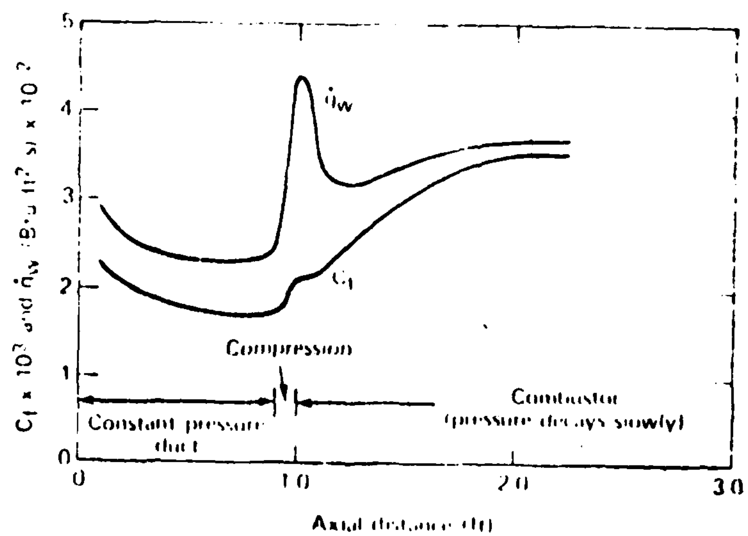
- PREDICTED AND ACTUAL WALL CONTOURS IN GOOD AGREEMENT
- H_2 AND CO FLAMES IN QUALITATIVE AGREEMENT WITH COMBUSTION PROCESS
- INSTREAM PROFILES NEEDED TO DESIGN EFFICIENT COMBUSTOR AND EXIT NOZZLE CONTOURS
- REVISED BASE FLOW AND THERMOCHEMISTRY MODELS NEARLY COMPLETE

COMBUSTOR BOUNDARY LAYER MODEL

- WALL FRICTION INCREASES WITH AXIAL DISTANCE OR HEAT RELEASE
- LARGE RISE IN HEAT FLUX AT SHOCK, GRADUAL RISE IN COMBUSTOR
- TRENDS AGREE WITH MEASUREMENTS IN SCRAMJET
- THERMOCHEMISTRY IMPROVEMENTS BEING ADDED



PREDICTED PROFILES ACROSS THE DUCT AT MACH 7 WITH ER = 0.5



COMBUSTOR WALL SKIN FRICTION COEFFICIENT AND HEAT FLUX DISTRIBUTIONS FOR M_0 = 7 FLIGHT FOR ER = 0.5

NAVY RESEARCH, DEVELOPMENT TRENDS AND RESEARCH NEEDS
IN THE AREA OF RAMJET COMBUSTION INSTABILITY

W. H. Clark
Naval Weapons Center
China Lake, California

ABSTRACT

During the past ten years the Naval Air Systems Command (NAVAIR) has sponsored exploratory development of small, integral rocket-ramjet engines for tactical, air-launched missiles. Currently emphasis is on lightweight (less than 1000 lbs), low volume (less than 12 inch diameter) missiles for both air-to-air and air-to-surface applications.

During the evolutionary development of smaller and more compact ramjet engines it was discovered that the liquid fueled ramjets are susceptible to high amplitude pressure oscillations due to combustion instabilities. Instabilities with frequencies below approximately 1000 Hz are of particular concern because of possible coupling between the inlet shock structures displacement and the combustors pressure oscillations. Indeed, several development engines have suffered significant performance degradation because of loss of inlet performance due to these combustion instabilities.

During the past fiscal year the Chief of Naval Research approved a joint NAVAIR/Office of Naval Research (ONR) program to investigate the fundamental phenomena associated with combustion instabilities in modern integral rocket-ramjets. This program will start in FY 84 and is intended to last for five years at which time, hopefully, research results will be available for application in the development community.

The technical objectives of the program are to: (1) Establish the chemical and gasdynamic processes which cause unsteady combustion, (2) verify rational control methods (either active or passive) for eliminating pressure oscillations, and (3) provide analytical methods for predicting propulsion stability. Important research issues that will be addressed during the program are:

What fuel related properties and fuel/air mixing methods contribute to stabilizing the combustion process?

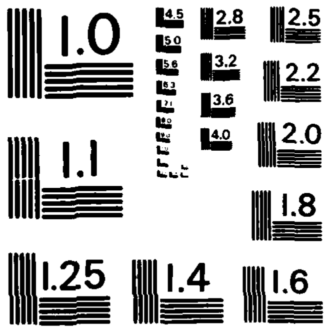
How can oscillations be suppressed by modifications to fuel chemistry or fuel injection?

How can the unique flow fields, large temperature gradients, and ramjets system geometry be accounted for in predicting limiting amplitudes of pressure oscillation?

What role do large scale gasdynamic processes have in providing and amplifying temporal and spatial delays in heat release and pressure fluctuations?

AD-A121 647 ABSTRACTS: 1982 AFOSR CONTRACTORS MEETING ON AIR BRETTHING COMBUSTION DYN..(U) UNIVERSITY OF SOUTHERN CALIFORNIA LOS ANGELES DEPT OF MECHANI..

UNCLASSIFIED M GERSTEIN ET AL. NOV 82 AFOSR-TR-82-0841 F/G 21/1 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Can pressure oscillations be suppressed by active control of vortex generation?

Can the response of inlet diffusers to high amplitude, low frequency pressure oscillations be theoretically modelled and experimentally verified?

Can the geometric scaling factors that promote high amplitude pressure oscillations in ramjet propulsion systems be identified?

Currently there are several on-going or planned research and development activities that specifically address some of these issues. In-house activities at the Naval Weapons Center, China Lake, are concentrating on experimental studies of instabilities in small scale combustors. The effects on instability characteristics of geometric scale, geometric configuration (single versus multiple inlets), fuel type, and acoustic/vortex shedding interactions are under investigation at NWC. At Cal Tech an analytical effort is underway to model the non-linear acoustic field in a ramjet with particular emphasis on predicting the limit of growth of pressure amplitudes. At the Naval Surface Weapons Center/White Oak Laboratories activities are concentrated on developing numerical models of the response of inlet shocks to downstream pressure disturbances. This inlet shock displacement phenomenon is also being studied experimentally at McDonnell Douglas Research Laboratories. During FY 83, in addition to continuing the above activities, a detailed plan will be developed by the NAVAIR/ONR managers for executing the total five year program.

MECHANISMS OF EXCITING PRESSURE OSCILLATIONS

IN RAMJET ENGINES (FQ8671-81-01162)

F. E. C. Culick, F. E. Marble, E. E. Zukoski, P.I.(s)

California Institute of Technology

Pasadena, California 91125

The aim of our work, which is being carried out in three complementary efforts, is to understand unsteady combustion processes in combustion chambers which are simplified models of several types of dump burners used in ramjet engines.

The first is an analytic study, by F. E. C. Culick and student, of combustion in a geometric configuration which includes the flow field of a simplified ramjet inlet and the burner. The field of interest extends from the terminal shock in the ramjet diffuser to the choked throat of the propulsion nozzle. A computer program is being developed which will allow us to study the influences of the steady flow field, the general features of the unsteady motion which accompanies the unsteady combustion process, and detailed representations of feed back mechanisms which are responsible for driving the instability. The second effort, by F. E. Marble and students, is a study of one of the driving mechanisms and it involves the transient combustion process and pressure field produced by a vortex which develops at the interface between hot burned products and unburned fuel-air mixture. The unsteady pressure field produced by this phenomena is responsible for one type of combustion instability observed in dump burners. The third effort, by E. E. Zukoski and students, is an experimental study of unsteady burning in a simplified dump burner configuration. The parameters under study include the pressure and velocity fields, the local heat release rates, and the flame front geometry for burners operating with and without instabilities. The burner is choked and is 2.5 cm high, 7.5 in. wide and 50 cm long.

The results of the latter two efforts will be used to support and guide the development of the computer program. The overall aim of these efforts is to develop the capability to scale experimental results and to suggest techniques which will allow us to develop propulsion systems which are not subject to combustion instabilities. Several results of these studies are described below.

The Steady Flow Field has been modeled by three regions separated by infinitesimally thin surfaces of discontinuity (Figure 1). Region 1 contains the flow of cold reactants which burn as they pass through the flame sheet; the hot combustion products flow to the exhaust nozzle located at the end of region 2. Flame stabilization is provided by the hot products in the recirculation region 3. This is essentially a pilot light anchoring the flame sheet at the lip of the dump plane. Regions 3 and 2 are separated by a stream surface across which the pressure is continuous but there is a discontinuity of the tangential velocity.

Figure 2 shows some numerical results for a typical calculation. The kinks in the shape of the flame sheet and in the velocity distribution occur at the axial location of the end of the recirculation zone. An integral method has been used to represent the flow field in regions 1 and 2, so disturbances necessarily propagate in directions transverse to the flow. The flow field in region 3 has been treated as an incompressible field with uniform vorticity.

Unsteady Flow Field; Linear Acoustics: It is the combustion processes and the form of the steady flow field which most obviously distinguish the class of problems we treat here from those of classical acoustics. As a first step we have carried out some calculations in which the uniform flow in the inlet duct and the unsteady response of the shock wave in the inlet diffuser have been accounted for. The combustion chamber is treated as a cavity with no combustion or flow. These have been done mainly to check the results against measurements being made at the Naval Weapons Center, China Lake. We have in the first instance been interested only in comparing the acoustic mode shapes, both amplitude and phase.

An example of the calculations is given in Figure 3. The most striking feature, and the one which motivated these results, is that the field in the inlet looks a bit like a travelling wave: the anti-node clearly is moving upstream during a cycle. This is a consequence of absorption of the leftward moving wave by the shock, and of the influence of the large ($M = .4$) mean flow speed. The pressure field is stationary, varying as $\exp(i\omega t)$ everywhere, but the phase distribution is non-uniform, giving an unfamiliar structure.

We have also obtained preliminary results incorporating the steady flow field described above.

Vortex Combustion Mechanism: A wide variety of combustion problems, including combustion instabilities and turbulent diffusion flames, appear to involve the entrainment and deformation of laminar flames by large vortex structures in the flow field. We have examined some details of this process of laminar flame distortion by considering the interactions of time-dependent diffusion flames with two-dimensional vortices. For large values of the recirculation parameter (the ratio of circulation to molecular diffusivity) Γ/D, the augmentation of the fuel consumption due to the vortex is proportional to $\rho\Gamma^{2/3}D^{1/3}$. When the effects of finite chemistry are included, the increase of fuel consumption rate is governed by a time scale which depends on a chemical reaction time, t_{ch}. Since the products of combustion occupy more volume than the original reactants, the spiral flame will appear as an unsteady volume dilatation for times on the order of the chemical time. This acts as an acoustic source and the interaction of a vortex and diffusion flame results in the generation of a pressure pulse. The peak pressure is proportional to $\Gamma^{2/3}D^{1/3}/\sqrt{t_{ch}}$ and occurs after a delay proportional to the chemical time, t_{ch}, as is shown in Figure 4. The results provide the fundamental structure for the mechanism of instability proposed by Rogers and Marble (1956).

The Experimental Program will be discussed at the meeting.

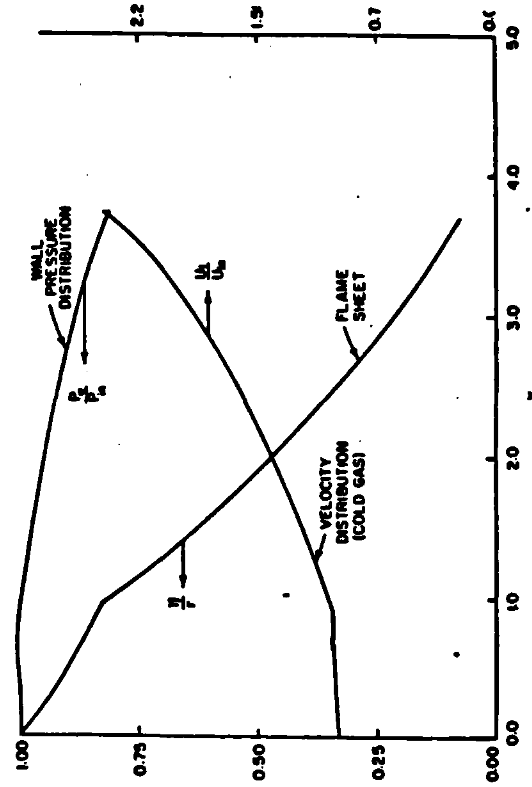


FIGURE 2.

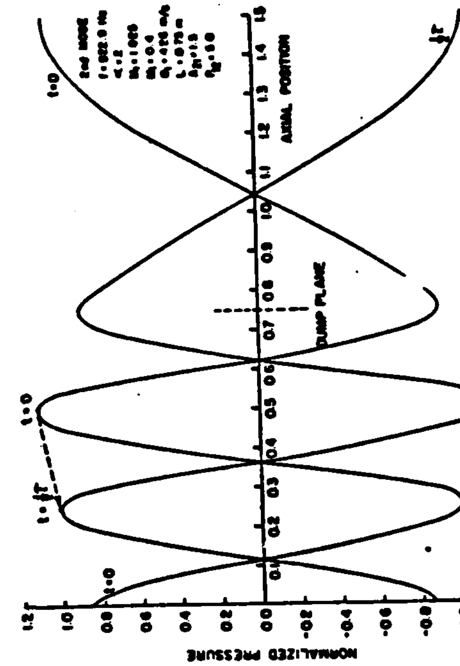


FIGURE 3.

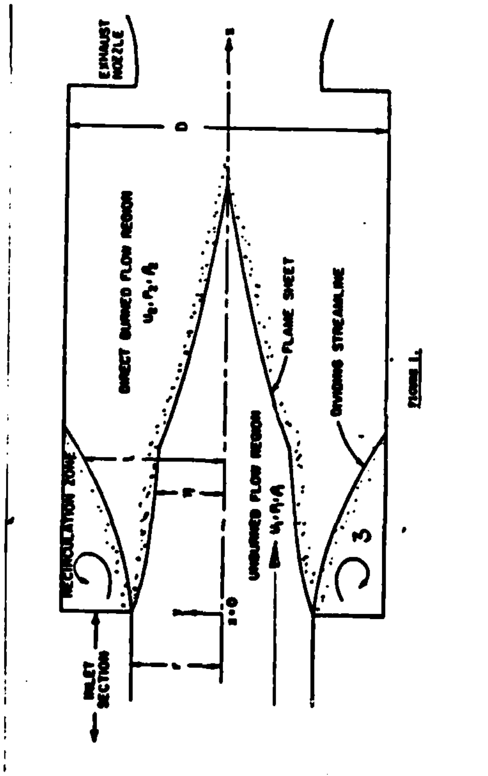
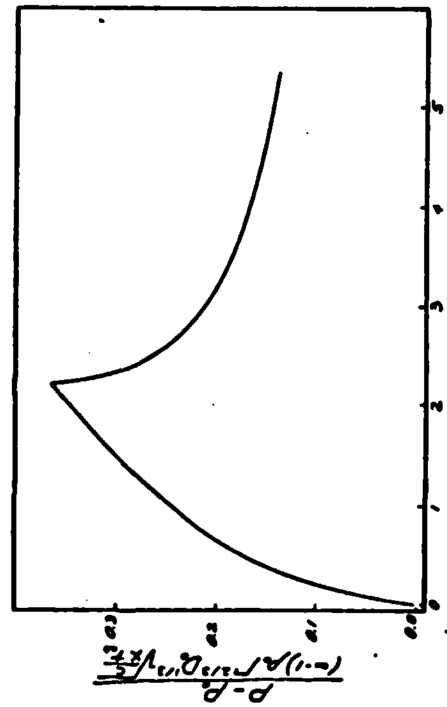


FIGURE 1.



<u>Figure 4.</u>
The pressure pulse seen at a distance x from the vortex, when x is large enough to lie in the far field

BASIC INSTABILITY MECHANISMS IN

CHEMICALLY REACTING SUBSONIC AND SUPERSONIC FLOWS

(AFOSR-78-3662)

Tau-Yi Toong

Massachusetts Institute of Technology

Cambridge, Massachusetts 02139

The main objectives of this research program are to determine the major mechanisms governing the efficiency, power output, stability, and pollutant emission of propulsion devices as well as safety against explosions. Two problems have been studied during the past year: one is related to the triggering and the sustenance of low-frequency instability in dump combustors and the second, the temporal development of turbulent combustion.

The attached two figures describe the technical approach and the accomplishments during 1981-82 on one of these two problems, the low-frequency instability in dump combustors. Such instability is believed to be triggered and sustained by interactions between non-uniform entropy zones and pressure waves. Figure 1A shows the generation of pressure waves as an entropy wave is convected through a choked nozzle and Fig. 1B shows the generation of the entropy wave as the pressure waves interact with the combustion zone. Instability characteristics of this model can then be computed by a linear analysis.

Figure 2A shows a comparison of the predicted frequencies with the measured values obtained at the Aero Propulsion Laboratory, AF Wright Aeronautical Laboratories, for three combustor lengths and diameters with and without a flameholder. The general agreement is quite satisfactory.

The effects of combustor configurations and inlet stagnation temperature on the amplification rates have also been predicted. Figure 2B shows that the amplification rates decrease with increasing ratio of combustor to inlet area or with increasing inlet stagnation temperature, other quantities being held constant. Other effects not shown include those due to changes in the nozzle-to-combustor area ratio and to the use of a flameholder. It will be reported at the Contractors Meeting that the amplification rates decrease with decreasing nozzle-to-combustor area ratio and with the use of a flameholder. These findings are found to be in qualitative agreement with the APL observations.

The second problem being studied is directed to the elucidation of turbulence-combustion interactions. During the past year, effort has been devoted to examine the growth of small disturbances or Tollmien-Schlichting waves in a reacting shear layer.

It is known that non-reacting, inviscid, shear layers are always unstable to normal-mode disturbances when the mean velocity profile has an inflection point. Recent work has shown that when exothermic, Arrhenius-type reaction is taking place in the shear layer, the growth rate of these disturbances is increased. The chemical effects depend on the order, the thermicity, and the activation energy of the reaction as well as the disturbance wave lengths and Damköhler's similarity parameters. These results will be presented at the OSR meeting.

MASSACHUSETTS INSTITUTE OF TECHNLOGY
LOW-FREQUENCY INSTABILITY IN DUMP COMBUSTORS

PRINCIPAL INVESTIGATOR:
T. Y. TOONG

MAIN RESULTS:

(1) PREDICTION OF INSTABILITY FREQUENCIES AND AMPLIFICATION RATES
(2) COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS
(3) INVESTIGATION OF EFFECTS OF DESIGN AND OPERATING PARAMETERS ON AMPLIFICATION RATES

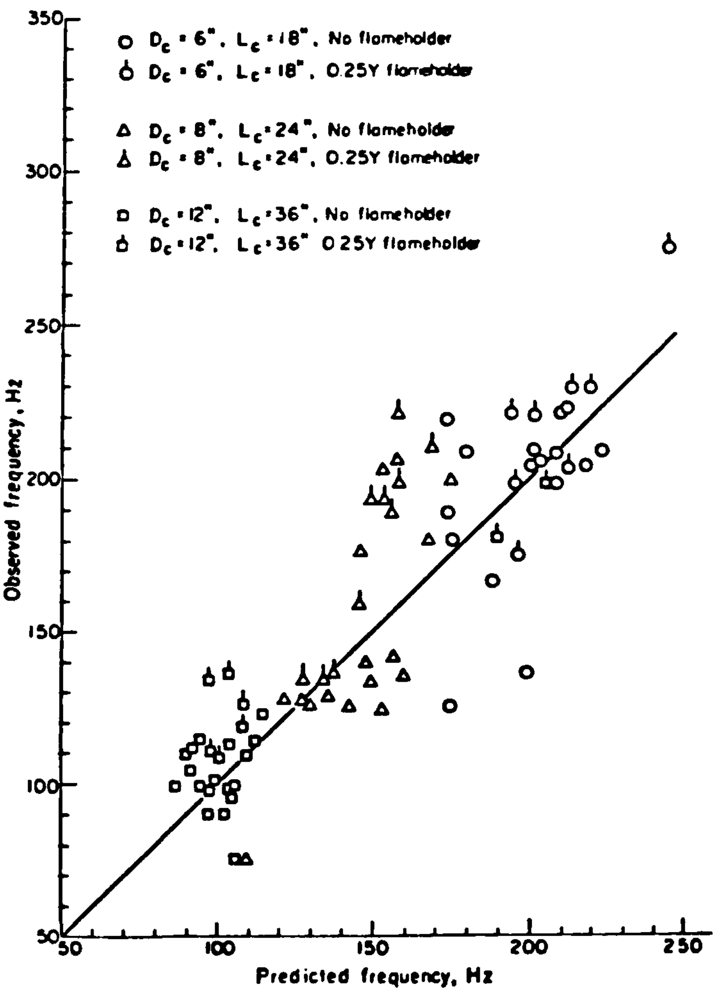


FIG. 2A COMPARISON OF PREDICTED AND OBSERVED FREQUENCIES

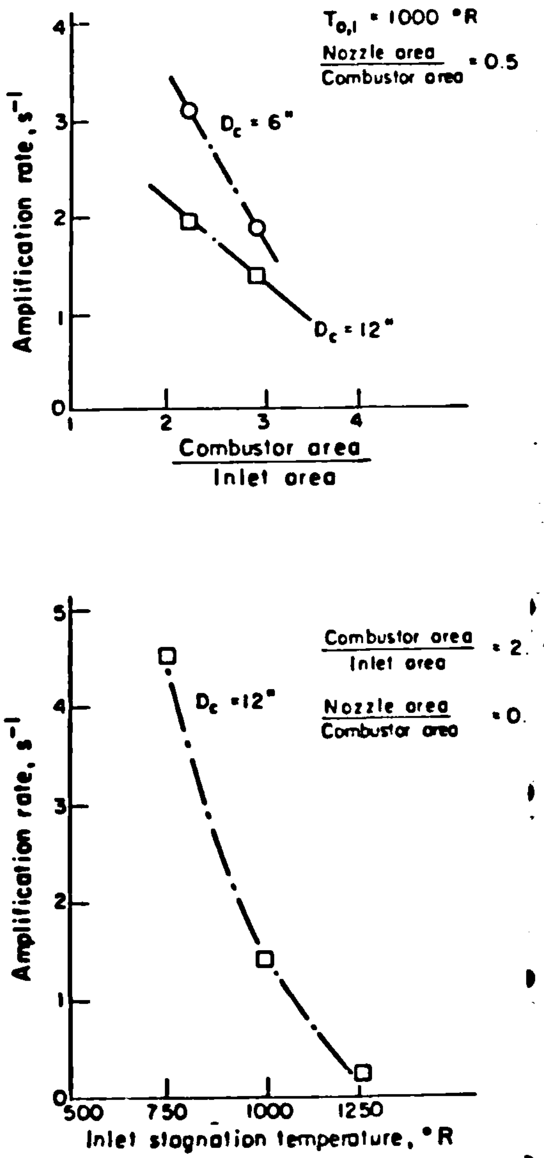


FIG. 2B EFFECTS OF DESIGN AI OPERATING PARAMETER: ON AMPLIFICATION RA

TECHNICAL APPROACH

ASSACHUSETTS INSTITUTE OF TECHNOLOGY
OW-FREQUENCY INSTABILITY IN DUMP COMBUSTORS

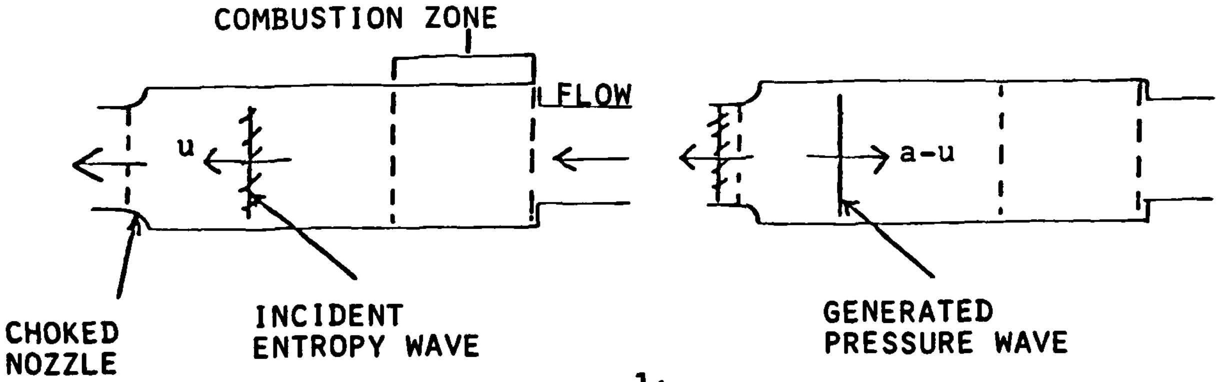
PRINCIPAL INVESTIGATOR:
T. Y. TOONG

BJECTIVES: TO DETERMINE MAJOR MECHANISMS GOVERNING TRIGGERING AND SUSTENANCE OF LOW-FREQUENCY INSTABILITY IN DUMP COMBUSTORS AND TO PROVIDE DESIGN BASIS TO ELIMINATE SUCH INSTABILITY

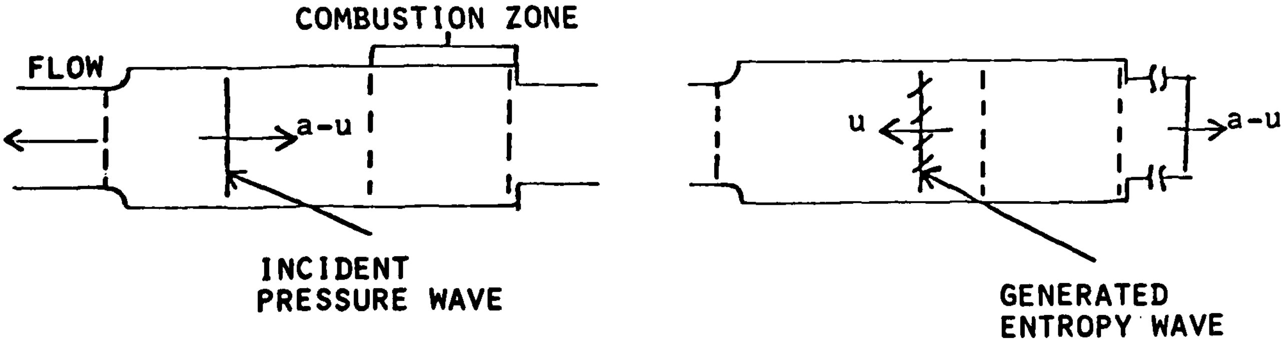
PROACH: TO STUDY THE INTERACTIONS BETWEEN NON-UNIFORM ENTROPY ZONES AND PRESSURE WAVES:

FIG. 1A GENERATION OF PRESSURE WAVES BY CONVECTION OF ENTROPY WAVES THROUGH A CHOKED NOZZLE

FIG. 1B GENERATION OF ENTROPY WAVES BY PRESSURE WAVES INCIDENT ON COMBUSTION ZONE



1A



1B

MODELING OF AUGMENTOR COMBUSTION INSTABILITY

R.C. Ernst

Pratt-Whitney Government Products Division

USE OF NEW AND ALTERNATIVE FUELS IN AIR-BREATHING GAS TURBINE AND RAMJET ENGINES

Charles R. Martel
Aero Propulsion Laboratory
Air Force Wright Aeronautical Laboratories (POSF)
Wright-Patterson Air Force Base, Ohio 45433

The Fuels Branch of the Aero Propulsion Laboratory is actively involved in fuels combustion research and related combustion programs. The Fuels Branch is responsible for the research, development, and field support of aviation turbine and ramjet fuels for the Air Force. This responsibility has led to our involvement in the following programs, each to be discussed separately: (a) use of fuels from alternative sources for conventional aircraft; (b) development and use of special high energy fuels for air-breathing missiles; and (c) fuel combustion research, combustion modeling, and combustion diagnostics (this latter work to be discussed in a separate presentation by Dr W. M. Roquemore).

Alternative Fuels. As light, high-quality petroleum crude oils decrease in availability, aviation turbine fuels will increasingly be produced from heavy crudes, oil shale, tar sands, coal, and possibly biomass. The ultimate objective of our ongoing advanced development program is to formulate an aviation turbine fuel specification that assures that any fuel meeting the specification will be completely suitable for use, regardless of origin and refining processes used. To prepare this ultimate specification, the combustion performance of fuels must be known. To this end, a wide range of fuels, including fuels blended to simulate products derived from shale, tar sands, and coal, have been tested in combustors representing the J-57/TF33, J-79, J-85, TF-41, F-100 and F-101 engines. Augmentor tests for the J-79, J-85, TF-30, and F-100 have also been conducted.

The tests with the wide spectrum of fuels and different engine combustors have provided information as to how different fuel properties and compositions affect the performance and durability of the combustors tested. Current combustor modeling and correlation capabilities do not allow the accurate extrapolation of these data to other engine combustors. Therefore, Purdue University's School of Mechanical Engineering and Pratt and Whitney Aircraft Division have been contracted to develop correlations and models to predict fuel effects on turbine engine combustors and hot section components. The fuel effects programs mentioned above will provide the data base. Preliminary results show promise of accurately predicting alternative fuel effects on other, untested combustors. The successful completion of these programs will eliminate much of the testing that will otherwise be required to qualify new fuels for aircraft turbine engine use. These correlations and models may also be used in specifying minimal acceptable combustion performance for the "ultimate" fuel specification mentioned above.

Early in 1983 we plan to conduct accelerated mission testing of the TF30 and F100 engines with an oil shale-derived JP-4 fuel. These tests will be followed by F111 and F16 flight tests with the shale JP-4. These tests should clear the use of production shale JP-4 scheduled to be delivered to two western bases beginning during the winter of 1983-84. This fuel will be refined from the crude shale oil produced by the 10,000 bbl/day Union Oil Company oil shale facility located in Colorado.

Alternative Fuels Research Needs

a. Better understanding of soot formation within combustors; the effects of fuel composition, combustor design, and operating conditions.

b. Improved combustion models that can predict fuel effects on combustor discharge temperature patterns.

Missile Fuels. The range of air-breathing cruise missiles such as the Air Force's AGM-86B Air Launched Cruise Missile (ALCM) and the Navy's BGM-109 Tomahawk is limited by the volume of fuel that can be carried. The Fuels Branch has developed special high-density liquid hydrocarbon fuels to extend the range of volume-limited missiles such as the ALCM. By using JP-10, the ALCM will have about 15 percent more range than if JP-4 were used. To further increase the volumetric energy content of fuels, we have initiated work to develop carbon slurry fuels for turbine engines. (Carbon slurry is actually a misnomer; these fuels consist of a stabilized suspension of submicronic carbon particles in a liquid hydrocarbon fuel).

Carbon slurry fuels for turbine powered missiles appear to be feasible and promise about a 20 percent increase in volumetric heat of combustion as compared to JP-10. Experimental carbon slurry fuels have been produced by Ashland Chemical Company, Suntech Corporation, and Exxon Research and Engineering Company. The formulation problems require a suitable compromise among the conflicting requirements of: (1) long storage stability; (2) low viscosity at -65°F; (3) high energy content per unit volume (i.e., high carbon loading), and (4) good combustion characteristics. Major variables include carbon particle type and size distribution, carbon loading, the type and amount of surfactant or gelling agent used, and the choice of carrier liquid.

Currently, Suntech Corporation is under contract to develop improved carbon slurry fuels. Their subcontractors, including Williams International and two aircraft companies, will demonstrate the combustion performance of these new formulations. Lessons learned will be applied to new slurry fuel formulations in an iterative manner. A separate contract with General Electric Company will result in the development of a small gas turbine engine combustor designed to burn carbon slurry fuel. Another contract with Pennsylvania State University (Dr G. M. Faeth) will examine the combustion performance of carbon slurry fuels employing catalysts and mixtures of different carbon particles sizes.

The use of boron slurry fuels in turbine engines is being investigated under Defense Advanced Research Projects Agency (DARPA) funded programs. Boron-based fuels promise volumetric energies of twice that of hydrocarbon fuels. Future work with boron fuels is planned.

Missile Fuels Research Needs

a. Understanding of carbon particle combustion, effects of carbon particle structure and method of production, and the selection of catalysts.

b. Methods to eliminate or prevent the agglomeration of the individual carbon or metal particles into larger clumps (i.e., agglomerates) that greatly increase the combustion time.

c. Improved injection and atomization methods for slurry fuels.

d. Methods to obtain high combustion efficiency for slurry fuels in combustors of reasonable size.

e. Methods to prevent or counter the deposition of boron oxides on turbine blades and other hot section components.

PROBLEMS IN THE COMPATIBILITY OF FUTURE FUELS WITH CURRENT AIR BREATHING COMBUSTION SYSTEMS

C.A. Moses, Manager, Fuels/Combustion Technology, Southwest Research Institute, San Antonio, Texas;
A.M. Mellor, Hess Chair Professor of Combustion, Drexel University, Philadelphia, Pennsylvania.

The U.S. Navy has undertaken the development of an "Alternate Test Procedure to Qualify New Fuels for Navy Aircraft" (ATP) to address the problems of operating aircraft on fuels for which they were not designed. This could be brought about by a change in the fuel specification to increase availability, the use of synfuels, or the use of non-specification fuels in emergencies. There currently is no accepted methodology of ensuring compatibility short of requalifying the hardware. Also, there are no means to predict the impact of the temporary use of non-specification fuels. The purpose of the ATP is therefore to reduce the number of large-scale engine and flight tests required to develop confidence that a new fuel type will perform satisfactorily without sacrificing performance, durability, and safety. The scope of this research program will be presented along with other supporting research conducted at SwRI in recent years on the effects of fuel properties upon combustion. The two major problem areas in combustion which are affected by fuels are soot formation and fuel-air mixing; the discussion will focus on these, but a few other areas will be mentioned for completeness.

Soot itself is only a problem if it is not oxidized within the combustor can and exits the engine as visible smoke. However, the presence of soot in the primary zone contributes heavily to the radiation heat load to the liner wall; the resultant increase in temperature will lead to a reduction in the life of the combustor. Usually the primary failure model of combustors is cracking due to low-cycle thermal fatigue (LCF); other failure modes include buckling and rupture, both caused by high temperature weakening of the metal. The objective of this program is therefore to *relate changing fuel properties to LCF life*. More specifically we are attempting to verify a model to predict the effects of reduced fuel hydrogen content on LCF life so that the model can be used to predict life reduction of combustors for which there is no liner temperature data available for varying fuels.

Recent experimental combustor studies at SwRI have been to identify the appropriate fuel properties that control soot formation in aircraft gas turbine combustors. A number of studies by SwRI and others have concluded that hydrogen content is the primary correlating parameter for flame luminosity in real engine combustion systems for fuels which do not contain significant amounts of multi-ring aromatics; however, the sensitivity to hydrogen content varies, among engine designs. Furthermore, some full-scale combustors exhibit an increased sensitivity to fuels containing tetralin and naphthalenes, while others do not. Recent laboratory scale combustor tests at SwRI show that the soot-forming tendencies of these multi-ring aromatics depend upon the operating conditions of the combustor such as pressure, inlet air temperature, stoichiometry, and reference velocity. These facts point out the need for such research to provide guidance for future engine designs to make them more tolerant of lower quality fuels, but also provide the caution for conducting the research in realistic combustion systems or at least to realize the limitations in applying the results.

Problems associated with fuel-air mixing are influenced by the atomization and the evaporation of the fuel; these are governed essentially by the viscosity and the boiling-point distribution of the fuel, respectively. The most serious problems are cold-day ignition and altitude relight. Combustion efficiency at low power conditions can be affected but is not usually considered a problem; similarly with lean blowout, flame structure, and exhaust-temperature pattern factor. The objective in the Navy program is to provide a model which can predict the effects of increasing fuel viscosity on ignition and relight limits of engines for which such data does not exist.

There are several levels of modeling used to address these problems in combustion performance ranging from empirical models, which would be valid only for the engine design that was tested, to finite difference models which currently can give only qualitative trend predictions. In between these are approaches such as the characteristic time models developed by Mellor, et al. These models are intended to be design independent by using "characteristic times" of appropriate phenomena in the fuel evaporation, mixing, and ignition history to permit correlation over different combustors. The essential parameters for ignition modeling are:

τ_{eb} ~ droplet evaporation time

τ_{HC} ~ a kinetic time for ignition delay

τ_{sl} ~ a mixing time in the shear layer

The first two characterize the heat-generation rate, while the mixing time controls the heat loss rate. This model is currently being applied by the authors to correlate ignition and altitude relight data from 12 engines for model validation. Using the finalized model, predictions in deterioration in cold start temperature limits and altitude relight ceilings will be made for the original 12 engines as well as eight additional engines for which there are no data for fuels of JP-5 volatility but with viscosities ranging from that of JP-5 to that of DFM.

One shortcoming that has been identified is a deficiency in atomization data, i.e., Sauter mean diameter (SMD). The fuel property correlation equations that are available for both pressure atomizers and air-blast atomizers were developed from data at atmospheric pressure. This is adequate for ground start conditions, but recent experiments at SwRI in a project for ONR indicates a significant pressure dependence. This would be especially important for any modeling of phenomena such as gaseous emissions, combustion efficiency, etc., at high pressure operation and for altitude relight at sub-atmospheric pressures. In the development of such data bases, there needs to be some concensus of where SMD should be measured since it changes with both radial and axial positions as droplets evaporate and as small droplets decelerate faster than large drops.

There are four other critical problem areas which are being addressed in the Navy program: fuel lubricity, thermal stability, materials compatibility, and peroxide formation during storage. While these are non-combustion problems, they are worth mentioning for a more complete understanding of the role of fuels in gas turbine engines.

Lubricity is a qualitative description about the relative abilities of two fluids having the same viscosity to resist friction and wear. It is apparently related to the presence of trace polar and surface active compounds in the fuel although the chemistry has not been defined. It is a potential problem because the hydrotreating processes used to remove sulfur and aromatics and to increase the hydrogen content of the fuel act to remove these trace compounds leaving a fuel that is better for combustion but poorer for pump life.

Thermal stability is a measure of the tendency for a fuel to form deposits under high temperature conditions. Thermal stability problems are generally long-term problems that affect overhaul time. The concern is over the possible emergency use of non-specification fuels which might foul atomizers relatively quick, which can affect ignition and other characteristics. The altering of fuel flow characteristics of one or more nozzles in a canular or annular combustor would degrade the exhaust temperature pattern factors and thus reduce the life of turbine blades due to high-cycle thermal fatigue. Empirical models are being developed for the more critical engines to predict fouling life for fuels of low thermal stability.

Aromatic content is controlled in jet fuels because of the solvent activity they have on certain kinds of elastomers, primarily Buna N. These materials are used extensively for O-rings, seals, and diaphragms. In some marketing areas there is a shortage of JP-5 which could be alleviated by relaxing the aromatic limit. There is also concern over the changing chemistry of fuels as crude sources and refining techiques change that introduce other "solvents" into the fuel that would not be controlled by a simple aromatic limit. The data base for making such decisions is being developed under this program.

Peroxides are not usually present in fuels when they leave the refinery. But fuels that have been severely hydrotreated tend to form peroxides during storage. A specification test for existing peroxides would not be effective; however, a test for potential peroxides needs to be developed.

It is believed that a more thorough understanding of how the chemical and physical properties of fuels affect the various aspects of engine performance and durability are necessary-both in the development of models and to provide design guidance for developing engines which are more fuel tolerant.

CHEMICAL KINETIC ISSUES ASSOCIATED WITH COMBUSTION-GENERATED EMISSIONS FROM CONVENTIONAL AND ALTERNATIVE FUELS IN AIR BREATHING ENGINES

Arthur Levy

Battelle, Columbus Laboratories
Columbus, Ohio 43201

The principal combustion-generated emissions from aircraft gas turbine systems are carbon monoxide, hydrocarbons, smoke (soot) and nitrogen oxides. CO and HC emissions occur mainly during engine idle conditions and at low load. These emissions result mainly from incomplete combustion and their formation is discussed mainly in terms of mixing procedures and residence times. Smoke is formed at high load when the fuel-air ratio in the combustor is at its maximum value. NO_x emissions from gas turbines are principally related to "thermal NO" until one considers alternative fuels, at which point prompt and fuel NO become significant. This presentation considers the chemical kinetics and mechanisms which influence the combustion-generated emissions.

The chemical and physical properties of alternative fuels and the role of combustor design are also considered in this discussion in terms of their influence on the chemical kinetics. Alternative fuels exert their biggest influence in terms of smoke and NO_x, the former due mainly to the higher aromaticity and lower hydrogen content, the latter due to the fuel-bound nitrogen. Smoke (soot) control is examined in terms of the six principal areas which make up a general mechanism for smoke formation. Also included are the role of additives and the role of water in the soot formation mechanism. NO_x formation mechanisms are separately evaluated for thermal, prompt and fuel NO_x. The roles of temperature, staging and mixing are examined in all three instances. Special attention is also addressed to the high levels of NO_2 in gas turbines and current thoughts on the kinetics behind the high NO_2/NO ratios.

AFESC SUPPORTED RESEARCH AND NEEDS ASSOCIATED WITH GAS TURBINE ENGINE EISSION AND OTHER COMBUSTION RELATED PROBLEM

Maj. T. Slankas & Capt. D. Berlinrut

AF Engineering Services Center/Tyndall AFB, Florida

ABSTRACT NOT AVAILABLE

In-Situ Optical Measurement of Additive Effects on Particulates in a Sooting Flame

P. A. Bonczyk
United Technologies Research Center
East Hartford, Connecticut 06108

INTRODUCTION

Soot occurs in a variety of combustion media and is almost always undesirable. For military aircraft, soot emissions produce a visible exhaust plume which makes the aircraft vulnerable to adversaries. In addition, soot interferes with the cooling of aircraft engine hot sections thereby reducing the durability of the engine. Fuel additives offer the potential of a convenient means of controlling soot. The difficulty is that additive mechanisms are poorly understood and, thus, sound criteria are not available for additive evaluation and selection. The main objective of this research is to develop a basic comprehension of additive mechanisms.

This work is an optical in-situ study of the effect of metallic additives on soot particulates in a laboratory-scale diffusion flame. The angular dissymmetry of Mie scattered laser radiation is used to determine particulate size and number density, from which the soot volume fraction is evaluated. The concentrations of additive atoms in the flame are important, and these are inferred from emission intensities of spectral resonance lines. Additive cations are important also, and their densities are evaluated assuming a Saha equilibrium between charged and neutral species. Results have been obtained for the alteration of soot particulate properties upon addition of alkali metal compounds to fuel rich and lean propane/oxygen/nitrogen flames, and significant reduction in soot volume fraction has been demonstrated. An explanation of these results is given within the framework of an ionic theory of soot formation.(1)

THEORY

Particulate size and number density may be determined from the angular dependence of scattered light intensity.(2) For radiation incident upon the particulates, the scattered light intensity is given by

$$I = (\lambda/2\pi r)^2 \langle\phi\rangle_{p,s}\, NV\Omega(I_o/A) \qquad (1)$$

where (Ir^2) is the scattered power at a distance, r; V, the scattering volume; Ω, the light collection solid angle; I_o, the incident power; A, the area of the incident beam of light; $\langle\phi\rangle_{p,s}$, a complicated function of size, refractive index, and scattering angle. The braces enclosing ϕ indicate that it is averaged over an ensemble of spheres of different size, and the subscripts "p" indicate that the function is sensitive to the polarization of the incident light. For a narrow size distribution, the ratio of the intensities at two different angles, θ_1 and θ_2, may be used to determine diameter in accordance with

$$I_s(\theta_1)/I_s(\theta_2) = \phi_s(\hat{n}, x, \theta_1)/\phi_s(\hat{n}, x, \theta_2) \qquad (2)$$

where the refractive index, $\hat{n}$, is known and the diameter, D, and the wavelength, λ, are in the parameter, $x=\pi D/\lambda$. Under these conditions, the ratio is a function of x alone and does not depend on the parameters Ω and V. The number density, N, is determined from Eq. (1) using $\phi_s(\theta_1)$ or $\phi_s(\theta_2)$ determined from Eq. (2).

EXPERIMENT

The apparatus used in this work is shown in Fig. 1. The burner is small-scale, circular, with three concentric slots through which flow fuel, oxidant and nitrogen shroud gases, respectively. A nebulizer, AT, is used to introduce metallic salts into the flame. The Ar^+ laser operates cw at 5145 Å with approximately 1W of power. The laser output is linearly polarized and the polarization direction may be continuously varied. Light scattered by the particulates in the flame is analyzed at 45, 90 and 135°. Each of the three light detectors is a photomultiplier tube, PMT. A 5145 Å narrow band optical filter, F, in front of the photomultiplier prevents luminous flame emission from reaching it. A polarization analyzer, PL, precedes the filter, and its orientation is that of the laser. Two apertures, A, are used to set the optical sample length and to limit the light collection solid angle. In order to measure the intensity of light emitted by excited, additives in the flame, a light collection system images the flame onto the spectrometer slit with unity magnification.

Particulate sizing measurements were made with and without additives for two, different $C_3H_8/O_2/N_2$ flames. For the first fuel-rich flame, the temperature was T=1973°K, whereas for the second leaner flame T=2173°K. Both flames were yellow and luminous, characteristic of soot formation. Scattering measurements were made at a vertical position equal to roughly two-thirds of the flame height. The dispersal of soot was inhomogeneous at this height, and measurements were made at the radial position corresponding to peak scattered intensity. Alkali chloride salts were tested as additives in the concentration range, 1×10^{-4} to 5×10^{-2}M (M=molar).

For the fuel-rich flame, the effect of increasing the additive concentration was to cause the particulate size to decrease and the number density to increase. This was most pronounced for the heavier alkali metals, which have low atomic ionization potentials leading to increased cation formation. Since the number of alkali atoms for a given molarity was approximately the same for all the alkali chlorides, the additive effectiveness is in direct relation to the number of alkali cations present. On the other hand, the results for, e.g., KCl added to the lean flame were significantly different. The particulates were smaller, of order 0.1μ diam, without an additive present. Similar to the above, the size decreased with KCl addition. The behavior of N was, however, different; it first increased to roughly twice its value in the unseeded flame, and then it decreased. The effect of the additive on the quantity of soot present was very pronounced, with (60-70) percent of it removed at the highest additive level.

The alkali cation densities were computed from the Saha equation using atom densities determined from resonance line emission intensities and flame temperature from a standard line reversal procedure. The dependence of the normalized soot volume fraction on cation density was evaluated for both flames and this is shown for K^+ in Fig. 2, wherein it is evident that K^+ ions are responsible for soot removal with an onset near, $N(K^+) = 2\times10^{11}cm^{-3}$.

DISCUSSION

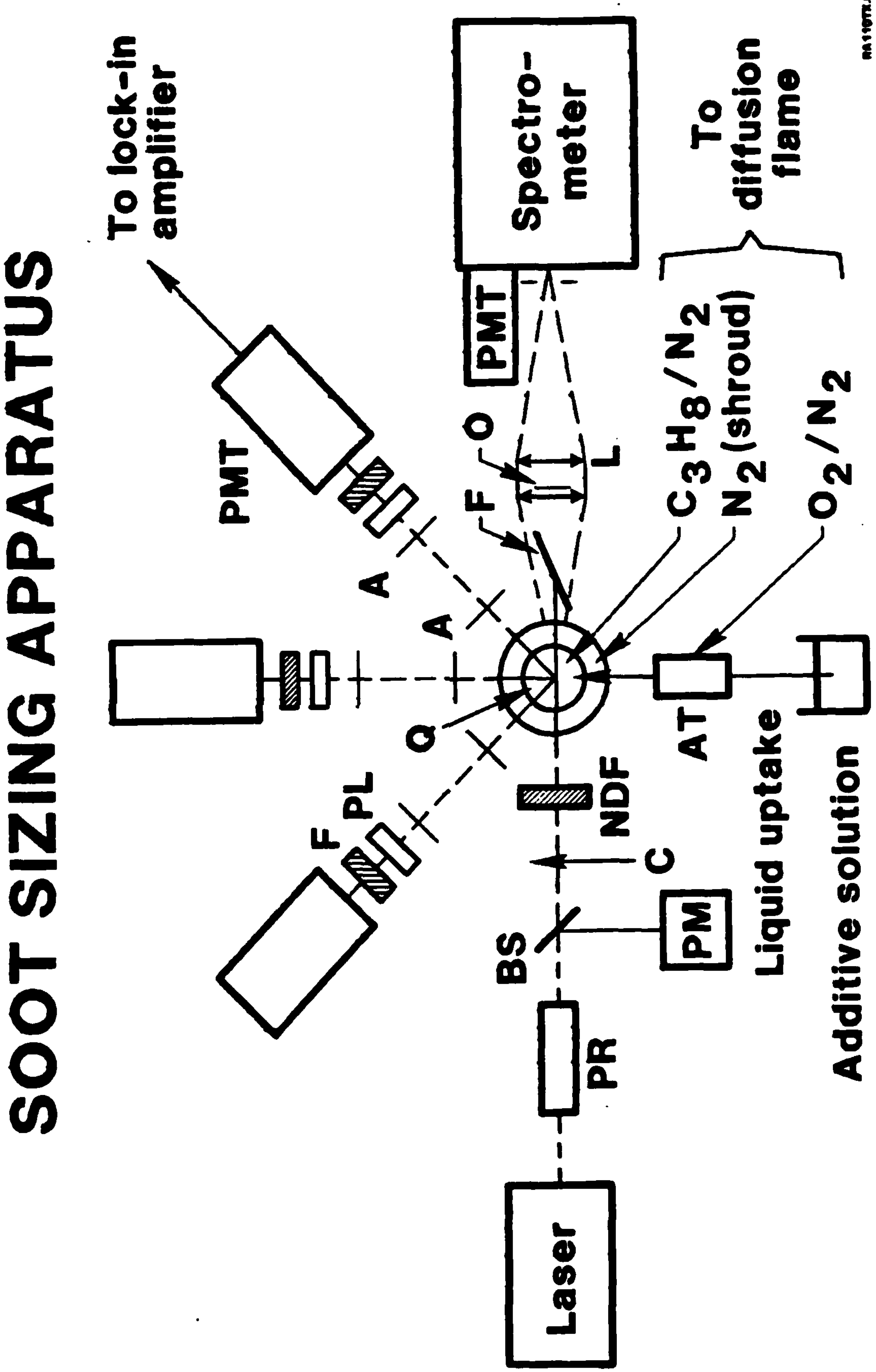
H_3O^+ are present in flames and may be regarded as primary ions critical to soot precursor formation and, hence, to soot onset.[1] Soot abatement in Fig. 2, which sets in at $N(K^+) \sim 2 \times 10^{11} cm^{-3}$, is due to the removal of H_3O by the additive. The additive molecule in the flame dissociates into an alkali and chlorine atom pair. Alkali cations are generated thermally via, $M \rightarrow M^+ + e^-$, where the M^+ and e^- at Saha equilibrium are present in equal concentrations. The H_3O^+ are neutralized in flames principally via, $H_3O^+ + e^- \rightarrow H_2O + H$. Accordingly, the ionization of the additive atoms leads to H_3O^+ removal, a reduction of soot precursors and, hence, a decrease in soot. The preceding is plausible provided that the number of K^+ ions exceed the H_3O^+ present. Hayhurst and Kittelson have shown that the peak H_3O^+ concentration in an atmospheric pressure $C_2H_2/O_2/N_2$ flame is in the range, 10^{10} to $10^{11} cm^{-3}$, and that the H_3O^+ persist well into the burnt gas region.[3] Taking this range of concentration as being roughly representative of this experiment as well, soot abatement occurs for, $N(K^+) \geq 2 \times 10^{11} cm^{-3}$, or where the (K^+, e^-) are present, indeed, in sufficient excess to perturb the H_3O^+. There is a region of K^+ densities in Fig. 2 for which the soot volume fraction is unaffected, i.e. $N(K^+) < 10^{11} cm^{-3}$. This may be explained in terms of ions as well. There, the (K^+, e^-) are not present in sufficient number to reduce H_3O^+. In this case, the additive acts to reduce the rate of particulate coagulation, leading to a decrease in particulate size and an increase in number density, but without altering the soot loading.

This experiment is the first completely in-situ measurement of additive effects in a diffusion flame. Earlier experiments were intrusive in regards to their sampling procedures, and/or were not specific in regard to particulate size and number density characterization. The present work complements the in-situ additive measurements reported for premixed flames.[4,5]

REFERENCES

1. Calcote, H. F., Combust. Flame 42, 215-242 (1981).
2. Bonczyk, P. A., Combust. Flame 35, 191-206 (1979).
3. Hayhurst, A. N., and Kittelson, D. B., Combust. Flame 31, 37-51 (1978).
4. Haynes, B. S., Jander, J., and Wagner, H. GG., Seventeenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, pp. 1365-1374 (1979).
5. Haynes, B. S., Jander, H., Matzing, H., and Wagner, H. GG., Combust. Flame 40, 101-103 (1981).

Figure 1



SOOT SIZING APPARATUS
To lock-in amplifier
PMT
Spectro-meter
PMT
To diffusion flame
RA1977.061
A
A
F
O
L
C_3H_8/N_2
N_2(shroud)
O_2/N_2
Q
PL
F
NDF
AT
C
BS
PM
Liquid uptake
Additive solution
PR
Laser

DEPENDENCE OF SOOT VOLUME ON K^+ NUMBER DENSITY

Flame: $C_3H_8/O_2/N_2$ diffusion

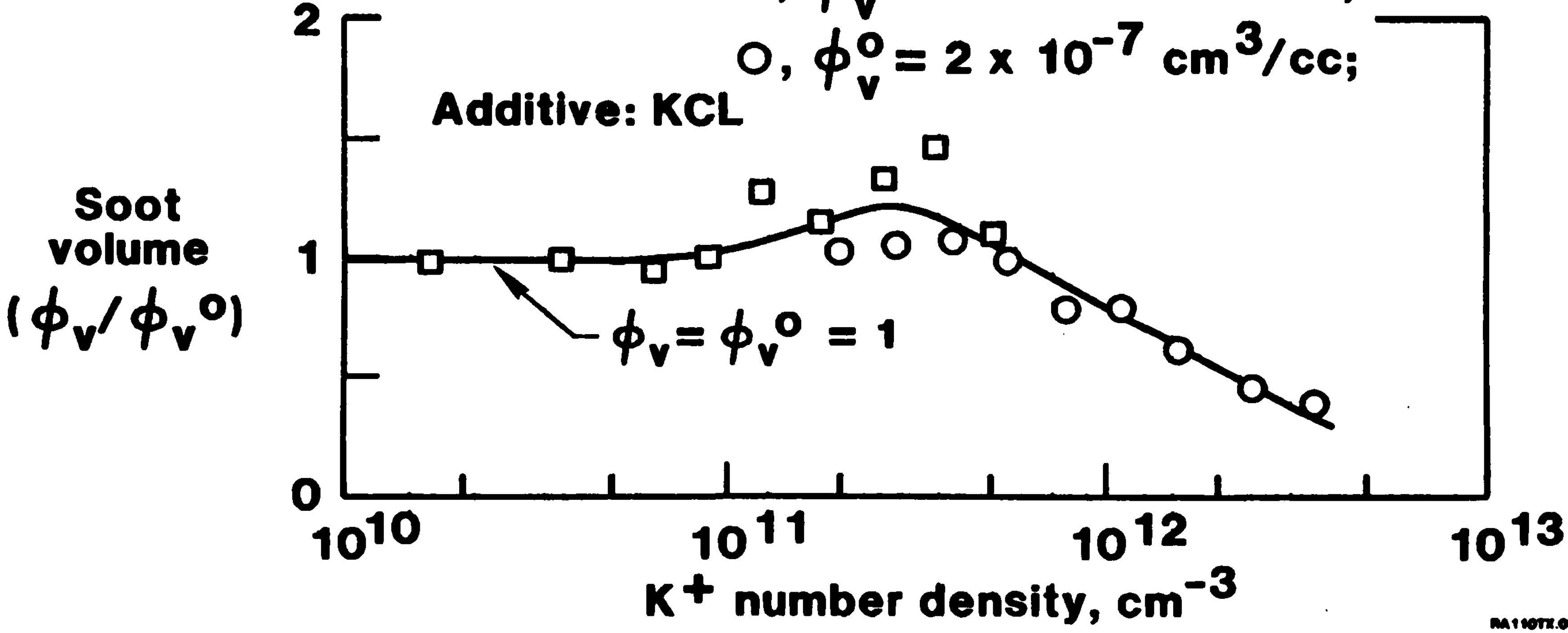
Temperature: □, T = 1973 °K; ○, T = 2173 °K

Equivalence ratio: □, ϕ = 1.35; ○, ϕ = 1.00

Soot volume: □, $\phi_v^o = 1 \times 10^{-6}$ cm^3/cc;

○, $\phi_v^o = 2 \times 10^{-7}$ cm^3/cc;

Additive: KCL



SOOT FORMATION PROCESSES AND OXIDATION OF AROMATIC HYDROCARBONS

Advanced Fuels Combustion Research

(AFOSR Contract No. F49620-82-K-0011)

Irvin Glassman, Frederick L. Dryer and Forman A. Williams
Principal Investigators

Department of Mechanical and Aerospace Engineering
Princeton University
Princeton, New Jersey 08544

In the coming decades fuel considerations for air breathing propulsion systems will be of prime importance to the Air Force. Princeton's program concentrates on combustion associated problems of advanced fuels. Since gas turbine fuels of the future will contain larger and larger concentration of aromatics, the possibility of soot and coke formation affecting gas turbine combustor can and turbine blade lifetime becomes of crucial concern and has been the focus of the current Princeton AFOSR effort. Similarily, in the realm of ramjet and other ducted systems, slurried fuels containing boron or carbon afford theoretical improvements in performance significant enough to warrant serious consideration of their combustion difficulties, thus studies of these advanced fuels have been integrated into the program and discussed in another abstract. Figure 1 depicts the gas turbine particulate problem and where the present problem applies.

Specifically, the ongoing effort studies the oxidation kinetics of aromatics (benzene, alkylated benzenes and polycyclic aromatics) by use of the turbulent flow reactor shown in Figure 2. The objectives are to provide understanding of soot formation processes, interactive effects in slurried fuel combustion and basic mechanisms for combustor modellers of aircraft gas turbine processes. The other aspect of the program tackles the problem of soot formation and destruction in pre-mixed and diffusion flame pockets such as those which exist in gas-turbine combustors. The results sought are a fundamental understanding of the soot process and the effect of physical (temperature, flow conditions, etc.) and chemical (fuel structure, additives, etc.) factors on the process. The experimental approach deals with accurate control of simple concentric diffusion and pre-mixed flame configurations in which the flame temperatures are controlled by inert gas addition to the vaporized fuels.

Extensive results have been obtained in both phases of the program and some of these results have been reported in two recent major publications [1,2]. Dealing with the question of aromatic oxidation, we reported last time that our initial results on the oxidation of benzene, toluene and styrene indicated that there were great similarities amongst the three in that the rate of oxidation was dominated by the phenyl radical formed in all three cases. We then proposed one of the first high temperature oxidation mechanisms of benzene or for purposes here of the phenyl radical. Observing the sequence of peaks of the intermediates (data which were shown in last year's abstract), we reported that the oxidation process begins by the phenyl radical reacting with O_2 in an exothermic chain branching step to form a phenoxy radical and an oxygen atom. The phenoxy isomerizes into the ketocyclohexadiene radical, which expels CO and forms a cyclopentadienyl radical, which reacts with O_2 in a manner analogous to phenyl and forms a compound which due to resulting delocalization of an electron forms a ketone radical. The stable form of this radical is 2 cyclopentene-1-one and was found in trace amounts in a mass spectroscopic examination of the reaction products. The radical was then postulated to once again follow the ring rupture step of CO expulsion and this time to form a butadienyl radical. The butadiene radical undergoes pyrolysis to form vinyl acetylene, acetylene and ethylene and an addition reaction to form butadiene. With respect to soot formation considerations this result is significant in that these four products of aromatic oxidation are all known to have a great tendency to soot. So it becomes apparent that the aromatics soot extensively not only because of their initial structure, but also because of the intermediates which form during their oxidation.

If there is great commonality among many of the aromatics, then the possibility of developing overall reaction mechanisms for a wide variety of compounds looked attractive. Such overall reactions would be of great importance to modellers. Consequently much of our recent work was directed to developing in more detail the complete oxidation mechanism of the alkyl part of the alkylated benzenes (essentially toluene and ethyl benzene). We had reported [1] that an early intermediate in toluene oxidation was benzaldehyde. The question of how benzaldehyde was formed was not definitive and particularly in light of recent results must be so considered. Refinement of our gas chromatographic analysis techniques to identify higher molecular weight compounds has permitted us to discover substantial amounts of dibenzyl, as shown in Figure 3. This observation is a good indication that the benzyl radical undergoes slow oxidative reaction steps similar to methyl radical oxidation. Due to its high endothermicity we now believe that the benzyl plus O_2 reaction is highly unlikely [3]. Recent experimental results would now indicate that the radical plus radical reactions of benzyl plus O, OH and HO_2 are the important paths to benzaldehyde formation and the relative significance of each individual oxidizing radical depends on its concentration which is a function of the equivalence ratio and temperature. As oxidation proceeds, benzyl plus O is definitely the more important reaction at lean equivalent ratios; rich equivalence ratios await further evaluation. As methane is unrepresentative of the general mechanism of alkane oxidation, it now appears that toluene is probably unrepresentative of alkylated aromatic oxidation [3].

More insight has also been obtained with respect to the oxidation of ethyl benzene. As reported [1] conversion of this aromatic fuel to styrene is extensive and extremely fast and suggests that under the driving force of attaining the highly delocalized styrene configuration, the second H atom is readily lost from the side chain. Significant amounts of ethylene are obtained too early in the reaction sequence to be from the usual oxidative decay of the ring into smaller fragments. Furthermore, the concentration profiles for the intermediates benzene and ethylene follow each other almost exactly and suggest, under our conditions of experimentation, cleavage of the unsaturated C_2 side chain may predominate over oxidative attack of the double bond. The benzaldehyde found could form as a result of the oxidation of benzyl radicals formed in the initiation process and thus its presence offers no direct evidence for the oxidation of styrene. However if benzaldehyde is produced from styrene then the interesting implication is that the process is quite like that of the oxidation of ethylene in that phenyl ethylene oxide forms. Steric factors would dictate that the oxide pyrolyze into benzaldehyde and a methylene radical rather than isomerize to phenylacetaldehyde. Work on ethyl benzene is proceeding and experimentation with α methyl naphthalene is about to begin. This latter polynuclear aromatic is more characteristic of the aromatics which make up aviation fuels.

Extensive new experimental results have been obtained in our program to assess the factors controlling the sooting tendency of fuels. In a series of publications [4,5,6] we believe we established temperature as one of the most important parameters in the rate of soot formation. For premixed flame systems, the extent of soot formation is controlled by the competition of the rate of formation of the soot precursors and the rate of oxidative attack [7]. As the temperature is raised, the rate of oxidative attack increases faster than the rate of soot precursor formation. Thus as the temperature increases in premixed system, the tendency to soot decreases. Since there is no oxidative attack on the fuel rich side of a diffusion flame where the soot precursors and soot form, the sooting tendency in diffusion flame systems increases as the flame temperature increases. Indeed it would appear that the rate and mechanism of fuel pyrolysis play a significant if not controlling role in determining the tendency to soot. In last year's abstract we reported much data on the sooting tendency under diffusion flame conditions. Additional data have been obtained and are shown in Figure 4. What we would like to stress this year with regard to these results are the data obtained for 1,3 and 1,4 cyclohexadiene. These fuels were chosen because the 1,3 is conjugated and the 1,4 is not and it was initially thought that the conjugated species would have the more noticeable tendency to soot. As seen, the experimental results do not indicate any difference and surprisingly the results fall on top of the benzene results. Review of the literature subsequently showed that the cyclohexadienes pyrolyze to benzene [8], and it is rewarding to note our experimental results show that all three compounds have the same tendency to soot. Indeed this result substantiates the postulate that the pyrolysis mechanism is important.

We have long argued that the generally accepted trend of sooting tendencies under diffusion flame conditions for aliphatic fuels: paraffins > olefins > acetylenes could not be correct in assessing the effect of fuel structure. Our kinetic results under this program had already established that under fuel rich premixed conditions the paraffins break down to the lower olefins and the olefins to acetylene [9]. Thus we are in the midst of extensive reevaluation of the type of data Street and Thomas [10] obtained, but again under conditions where the temperature of the flame is controlled. Much pre-mixed flame data have been obtained and an initial attempt at a plot of these data is shown in Figure 5, where the sooting equivalence ratio is plotted as a function of temperature. The smaller (leaner) the equivalence ratio (ϕ), the greater is the tendency to soot. There are many interesting observations to be made by examining Figure 5. First note that the cross points on every fuel represents the results for air. One thus observes for air, that acetylene has the least tendency to soot, ethylene next and than ethane, exactly the same as the early trend reported criticized and in agreement with Street and Thomas' results [10]. However, note that for a fixed temperature acetylene has the smallest ϕ for C_2 hydrocarbons. This trend is unrealistic. We had suggested earlier [4] that because premixed sooting data are in the very rich region that a more appropriate equivalence ratio would be one based on all carbon going to CO not CO_2 and the hydrogen still going to water. Figure 6 is a replot of the data in which the ordinate is an expression of this new equivalence ratio. The data taken on a much more logical trend, but there still appears to be an effect of the number of carbon atoms present. This trend would appear to indicate that the oxidation mechanism in premixed flames is playing a role. This work is continuing at the present time to obtain better understanding and results on aromatics.

References

1. Venkat, C., Brezinsky, K. and Glassman, I., "High Temperature Oxidation of Aromatic Hydrocarbons", to appear in 19th Symposium (Int'l) on Combustion, The Combustion Institute, Pittsburgh, PA.

2. Glassman, I., Brezinsky, K., Gomez, A. and Takahashi, F., "Physical and Chemical Effects in Soot Formation", to appear in "Recent Advances in Aerospace Sciences", Ed. C. Casci, Plenum Press, New York.

3. Litzinger, T., Brezinsky, K. and Glassman, I., "Some Further Results on the Toluene Oxidation Mechanism", to be presented at Eastern States Section/The Combustion Institute Meeting, December 1982, Atlantic City, NJ.

4. Glassman, I., "Phenomenological Models of Soot Processes in Combustion Systems", AFOSR TR-79-1147 (1979).

5. Glassman, I. and Yaccarino, P., "The Temperature Effect in Sooting Diffusion Flames", 18th Symposium (Int'l) on Combustion, The Combustion Institute, Pittsburgh, PA, p. 1175 (1981).

6. Glassman, I. and Yaccarino, P., Combustion Science and Technology 24, 107 (1980).

7. Millikin, R.C., J. Phys. Chem. 66, 784 (1962).

8. James, D.G.L. and Stuart, R.D., Trans. Faraday Soc. 64, 2752 (1968).

9. Dryer, F.L. and Glassman, I., "The Combustion Chemistry of Chain Hydrocarbons", in "Alternative Hydrocarbon Fuels", AIAA Series in Astro. and Aero., Vol. 62, p. 255, AIAA, New York (1978).

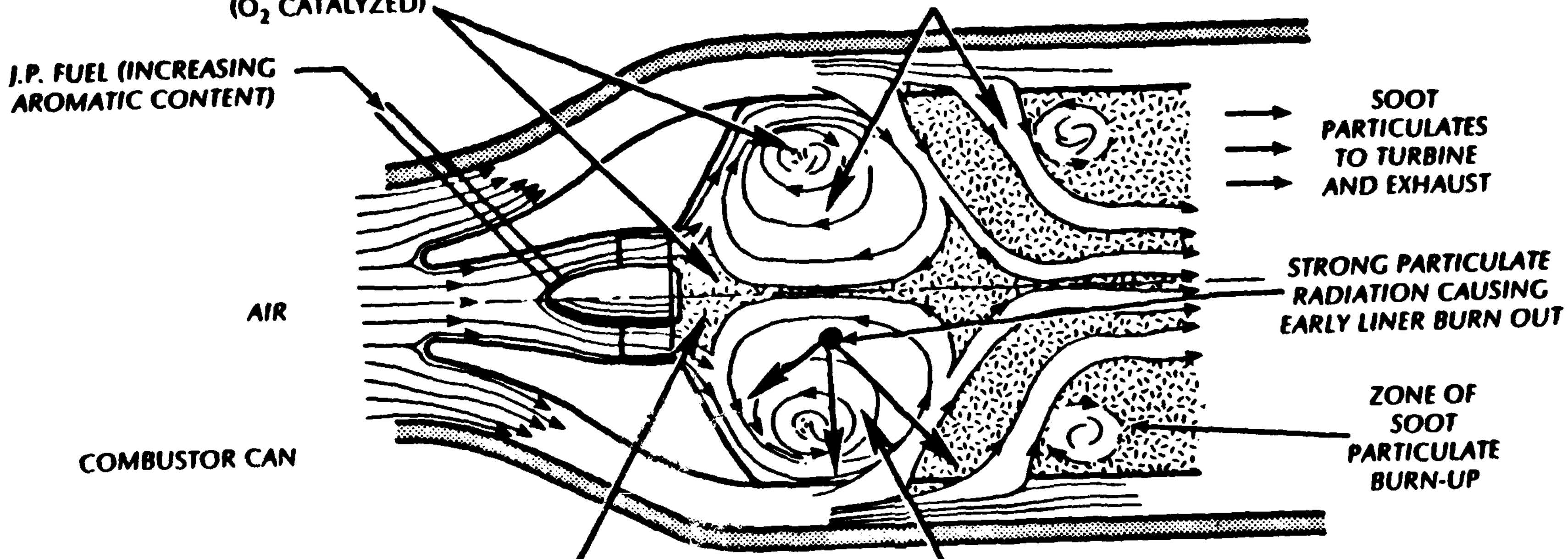
10. Street, J.C. and Thomas, A., Fuel 34, 4 (1955).

PRINCETON'S FUEL COMBUSTION RESEARCH AS RELATED TO AIRCRAFT GAS TURBINE COMBUSTOR PROBLEMS

TO UNDERSTAND MECHANISM OF SOOT PRECURSOR FORMATION, AND RADIATION, GASEOUS EMITTERS, AND EFFICIENCY EFFECTS

- LAB APPROACH — FLOW REACTOR FUEL PYROLYSIS STUDIES (ALSO WITH O_2 ADDED)
- REGION OF GAS PHASE PYROLYSIS OF FUELS (O_2 CATALYZED)

- LAB APPROACH — FLOW REACTOR FUEL OXIDATION STUDIES
- REGION OF GAS PHASE OXIDATION OF FUELS (AROMATIC & ALIPHATIC)



- LIQUID AND GASEOUS DIFFUSION FLAME ZONE (ZONE OF SOOT FORMATION)
- LAB APPROACH — OVER VENTILATED DIFFUSION FLAME SMOKE POINT EXPERIMENT WITH TEMP. CONTROL

- PREMIXED AND DIFFUSION FLAME POCKETS OF GASEOUS FUEL AND AIR (ZONE OF SOOT FORMATION)
- LAB APPROACH — BUNSEN BURNER SOOTING EQUIVALENCE RATIO EXPERIMENT WITH TEMP. CONTROL

TO DETERMINE EFFECT OF FUEL STRUCTURE AND TEMP. ON SOOT FORMATION

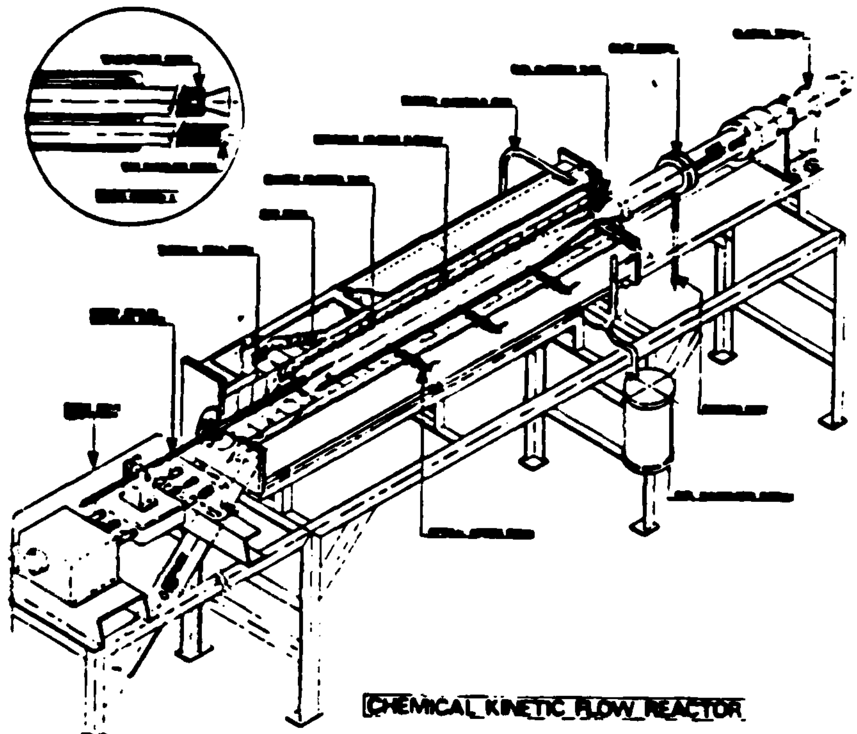


FIGURE 2

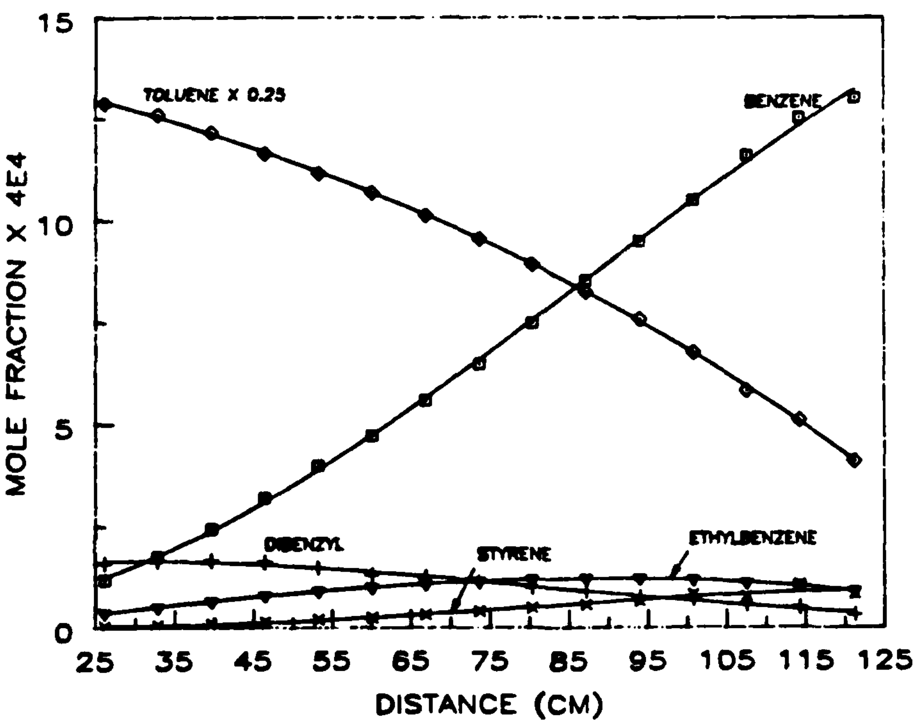


FIGURE 3

Fuel consumption and formation of products in Toluene oxidation at $\phi = 0.63$ and T $\cong$ 1180 K versus distance from fuel injection point.

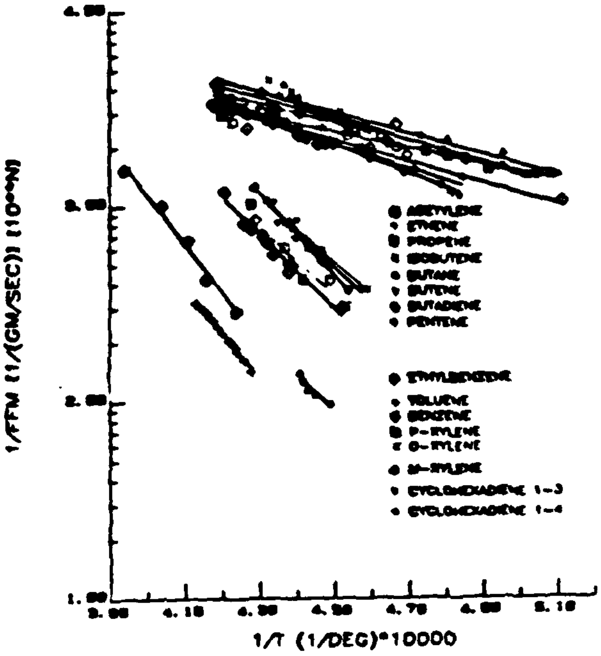


FIGURE 4
The sooting mass flow rate - temperature dependency plotted as Arrhenius parameters for various fuels under diffusion flame conditions.

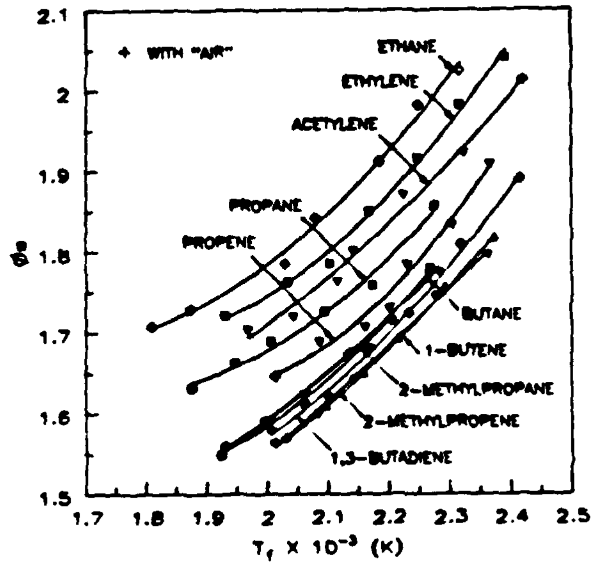


FIGURE 5
Sooting equivalence ratios for various fuels in pre-mixed flames as a function of temperature. Equivalence ratio based on carbon conversion to CO_2.

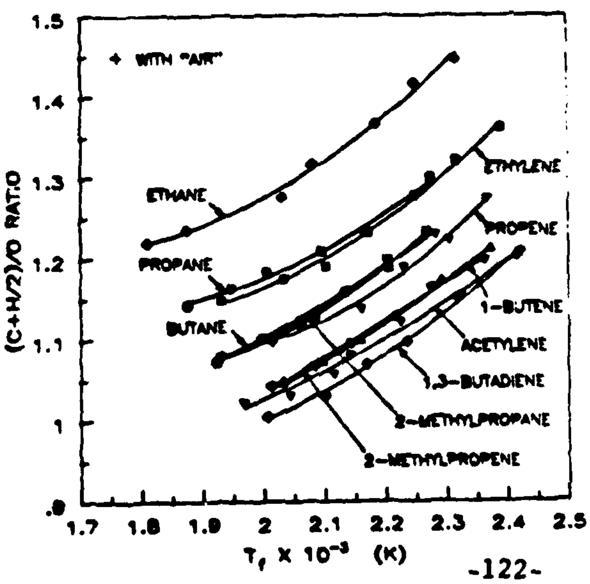


FIGURE 6
Sooting equivalence ratios for various fuels in pre-mixed flames as a function of temperature. Equivalence ratio based on carbon conversion to CO.

MECHANISMS OF EXHAUST POLLUTANT AND PLUME FORMATION
IN CONTINUOUS COMBUSTION
(AFOSR-78-3586)

G.S. Samuelsen

UCI Combustion Laboratory
Mechanical Engineering
University of California, Irvine

INTRODUCTION

The present analytical and experimental investigation is designed to clarify the relative influence of the physical and chemical processes responsible for gaseous pollutant and soot production in continuous combustion, and to develop and evaluate predictive methods for characterizing reacting flows. The results of the research will aid in establishing guidelines and techniques for reducing adverse environmental effects associated with conventional and as well as alternate and broad specification fuels in present and advanced jet engine combustors by control and modification of the combustion dynamic processes and use of fuel additives.

The approach (Figure 1) is to use model laboratory test combustors in combination with non-intrusive laser diagnostics to obtain detailed flow data. These data are then combined with theoretically predicted values to (1) identify the role of mixing and chemistry in the production of gaseous pollutants and soot in complex flows, (2) evaluate the numerical methods, and (3) establish data bases in support of the evolution of numerical codes and new optical diagnostics. A major effort is directed to the development of a common test bed for recirculating flows for the development of models and diagnostics.

Two-color laser anemometry is employed to measure simultaneously the two components of velocity and hence Reynolds stress. Dynamics of the combustion processes are addressed with high speed photography in combination with tracers to assess fuel jet penetration and subsequent mixing with the oxidant stream. Extractive probes are employed for gaseous species and partiulate sampling, and GC/MS, atomic absorption, and CHN analyses are used for particulate composition. Fuels include both gases and liquids, the latter of which are introduced as prevaporized or liquid sprays. Techniques for insitu measurement of droplet size and droplet velocity are being introduced for cold flow spray characterization and reacting flow droplet behavior.

RESULTS

A primary accomplishment during the current year is a detailed characterization of the Dilute Swirl Combustor (DSC). Both single component and two-color laser anemometry have been employed to document the flow structure over a broad range of operating conditions including reacting and non-reacting, 0-100% swirl, and both gaseous and liquid fuel spray injections. In addition, a state-of-the-art elliptic code was successfully configured to the DSC geometry and high speed cinematography was employed to visualize the flowfield dynamics. Results were presented at the AIAA/ASME Fluids, Plasma, Thermophysical, and Heat Transfer Conference (ASME Paper 82-HT-36), the AIAA/SAE/ASME Joint Propulsion Conference (AIAA Paper 82-1263), and the Fall 1982 meeting of the Western States Section, Combustion Institude (WSS/CI Paper 82-53). Temperature measurments are presently in progress.

The non-intrusive two-color laser anemometry used to characterize the Dilute Swirl Combustor is an important first step toward the establishment of a 'pool' of benchmark data on a common complex flow test bed geometry that can be used to 1) evaluate turbulence models, and 2) enhance the general understanding of turbulent processes in practical complex flows. A technique was used to obtain a direct measurement of Reynolds stress ($\overline{u'w'}$); peak correlation coefficients were on the order of 0.25 (Figure 2) which is less than that reported by others (0.40) using indirect measurement methods on somewhat different complex flow geometries. Direct comparison of the two measurement methods on a common geometry is needed to determine the quantitative accuracy of the indirect method. Root-mean-square velocity results indicate that for this flow u-w isotropy is a reasonable engineering assumption. Except in a few regions (e.g., the area of the fuel jet), the values of u_{rms} and w_{rms} are generally within 20%. The effect of reaction was to increase turbulence intensity levels and the equivalence ratio was observed to have a significant effect on the size and form of the recirculation zone. Fuel injection techniques indicate that "tailoring" fuel distribution to the recirculation zone shape is important in controlling soot production. In the present work, quantitative flowfield measurements verify that the increased visible soot production at higher equivalence ratios corresponds with a deflection of part of the fuel jet towards the relatively oxygen deficient core of the recirculation zone. Fuel injection techniques which insure the placement of fuel into the outer shear layer of the recirculation zone reduce the dependence of sooting propensity on equivalence ratio. There is evidence of 'form intermittency' of the recirculation zone which can take one of two forms 1) a spiralling action of the vortex center and 2) a fluctuating interaction between the fuel jet and the recirculation zone. The magnitude of this intermittency, particularly the latter, appears to be greatest with reacting flow and a function of equivalence ratio. When measured with a stationary LA probe, this form intermittency manifests itself in the form of increased turbulence intensity levels; it is thought that this component tends to 'dilute' the Reynolds stress correlation.

The DSC has also been introduced for use in a program conducted for the AFESC/RDV to address the formation of soot in aerodynamically complex flows. An optical and an extractive probe are employed to measure in-situ soot size, number density, and composition for a range of fuel blends comprised of iso-octane and ring hydrocarbons of increasing complexity. The centerbody combustor configuration was also employed earlier this year to assess the effect of fuel molecular structure on the physical and chemical properties of soot. Results were presented at the International Gas Turbine Conference (ASME Paper GT-82-109).

Finally, single component data have been acquired in a dump combustor configuration for both non-reacting and reacting flows in support of an element of the AFOSR program sponsored by the AFAPL/PORT. The goal is to obtain a data set for velocity and turbulence intensity that can serve as a foundation code development and evolution.

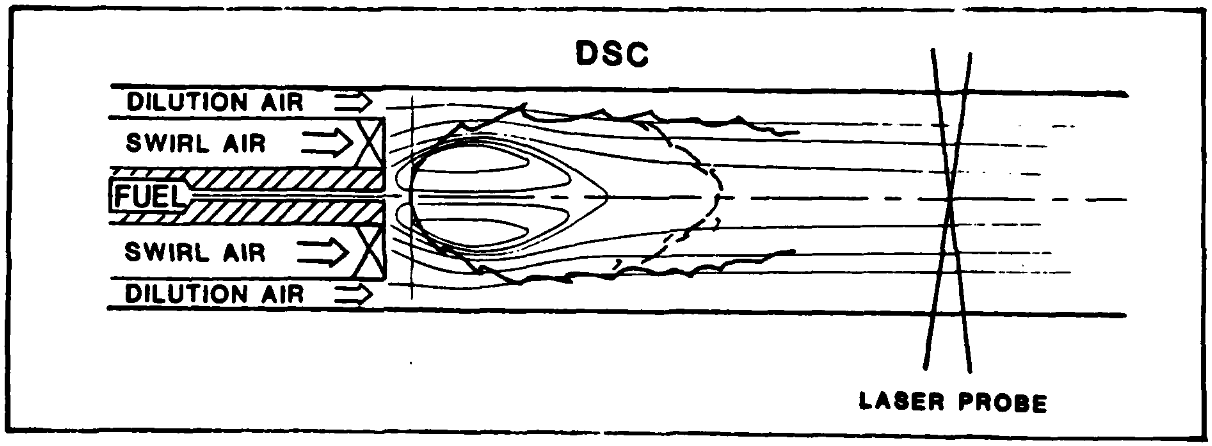
COMBUSTOR DYNAMICS

PROBLEM

- COMBUSTORS CHARACTERIZED BY COMPLEX (I.E., TURBULENT, RECIRCULATING FLOWS)
- PERFORMANCE, SOOT PRODUCTION REQUIRES IMPROVED UNDERSTANDING
- NON-INTRUSIVE DIAGNOSTICS IN INFANCY OF DEVELOPMENT
- MODELING LIMITED IN ABSENCE OF DETAILED INFORMATION

NEEDS

- MEASUREMENT OF FLUCTUATING PROPERTIES
- TESTS FOR PERIODICITY AND LARGE STRUCTURE
- DATA BASE
- COMMON TEST BED FOR
  - MODEL VALIDATION
  - DIAGNOSTIC DEVELOPMENT
  - MODEL AND DIAGNOSTIC CALIBRATION
  - COMBUSTOR DYNAMICS STUDIES
  - FUELS EFFECTS STUDIES



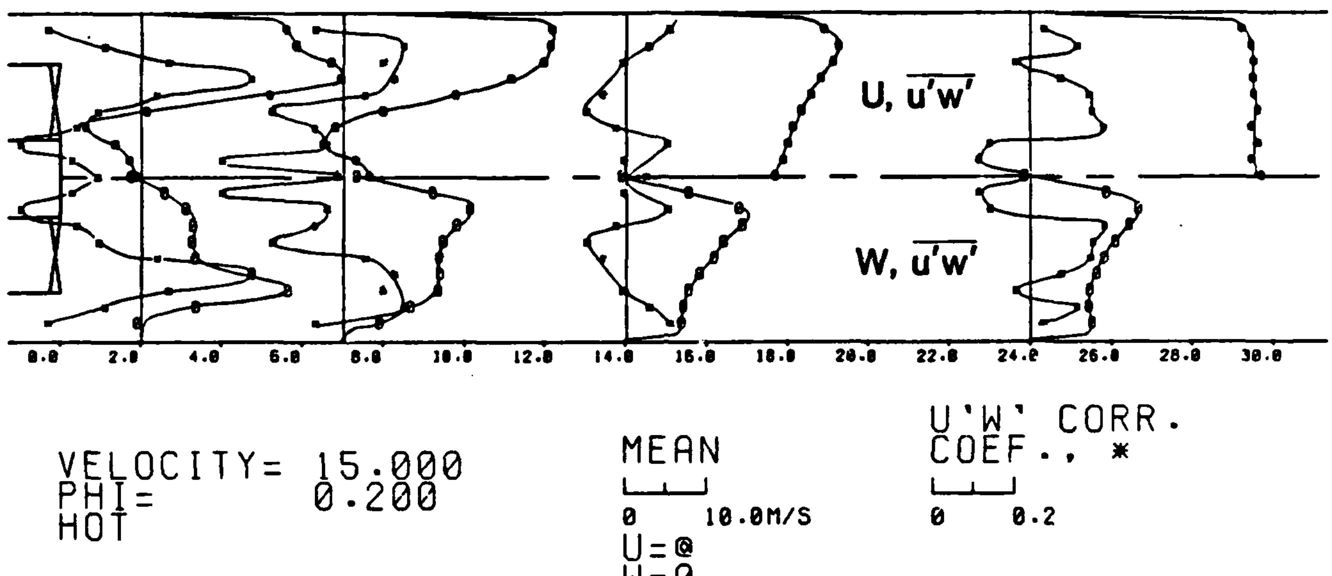
APPROACH

- CANDIDATE CONFIGURATIONS FOR COMMON TEST BED
- SPATIALLY AND TEMPORALLY RESOLVED MEASUREMENTS
- OPTICAL DIAGNOSTICS (VELOCITY, REYNOLDS STRESS, SOOT, DROPLET SIZE/VELOCITY)
- STEPWISE INTRODUCTION OF COMPLEXITY (COLD, HEATED, HOT, FUEL SPRAY)

TURBULENT MIXING

TWO-COLOR ANEMOMETRY

●U-VELOCITY ●W-VELOCITY ●u'w'-REYNOLDS STRESS	●Uref = 15 mps ●ϕ = 0.2 (PROPANE)



(BRUM AND SAMUELSEN, 1982)

- DESCRIPTION OF TURBULENT MIXING
- DATA BASE FOR MODELING
- MEASURE OF ISOTROPY
- DATA BASE FOR DIAGNOSTICS CALIBRATION
- ASSESSMENT OF FUEL DISTRIBUTION
- ASSESSMENT OF FUEL PROPERTIES

THE BEHAVIOUR OF DETONATION WAVES IN SINGLE PHASE HETEROGENEOUS SYSTEMS (81 - 0247)

D.H.EDWARDS

DEPARTMENT OF PHYSICS, UNIVERSITY COLLEGE OF WALES,

Aberystwyth, Wales, U.K. SY23 3BZ

Studies on the initiation and propagation of detonation waves in confined, or partially confined, fuel/air systems generally assume that such systems are of homogeneous composition. In practice large variations of fuel concentration in air will arise from imperfect mixing and in large vapour clouds the concentration of the fuel in air will vary from 100% to zero at different locations in the cloud. Extensive concentration gradients will thus occur throughout the whole volume and these will significantly influence both its deflagrative and detonative properties. The primary objective of this work is to study, firstly, in a detonation tube, the interaction of a detonation wave with both abrupt and gradual changes in the concentrations of fuel in air. When these wave processes are fully understood the work will be extended to examine the behaviour of a detonation propagating through two concentration gradients at varying separation. The final goal of the study is to elucidate the effect of these wave interactions on the detonability of an unconfined fuel/air cloud.

A sketch of the detonation tube, which is mounted vertically, is given in figure 1. It consists essentially of an initiating section 60 cm long, a run-up, or 'donor', section 300 cm long, and an observation section which can accommodate either an optical window or a smoked-foil holder, the latter being used to examine the cellular structure of the waves. On either side of the observation section are the two removable slides which allow any concentration gradient to be set-up by diffusion; for this purpose the length of the observation section can be varied. Wave velocities are measured by a microwave interferometer and the tube is equipped with a number of piezoelectric pressure gauges.

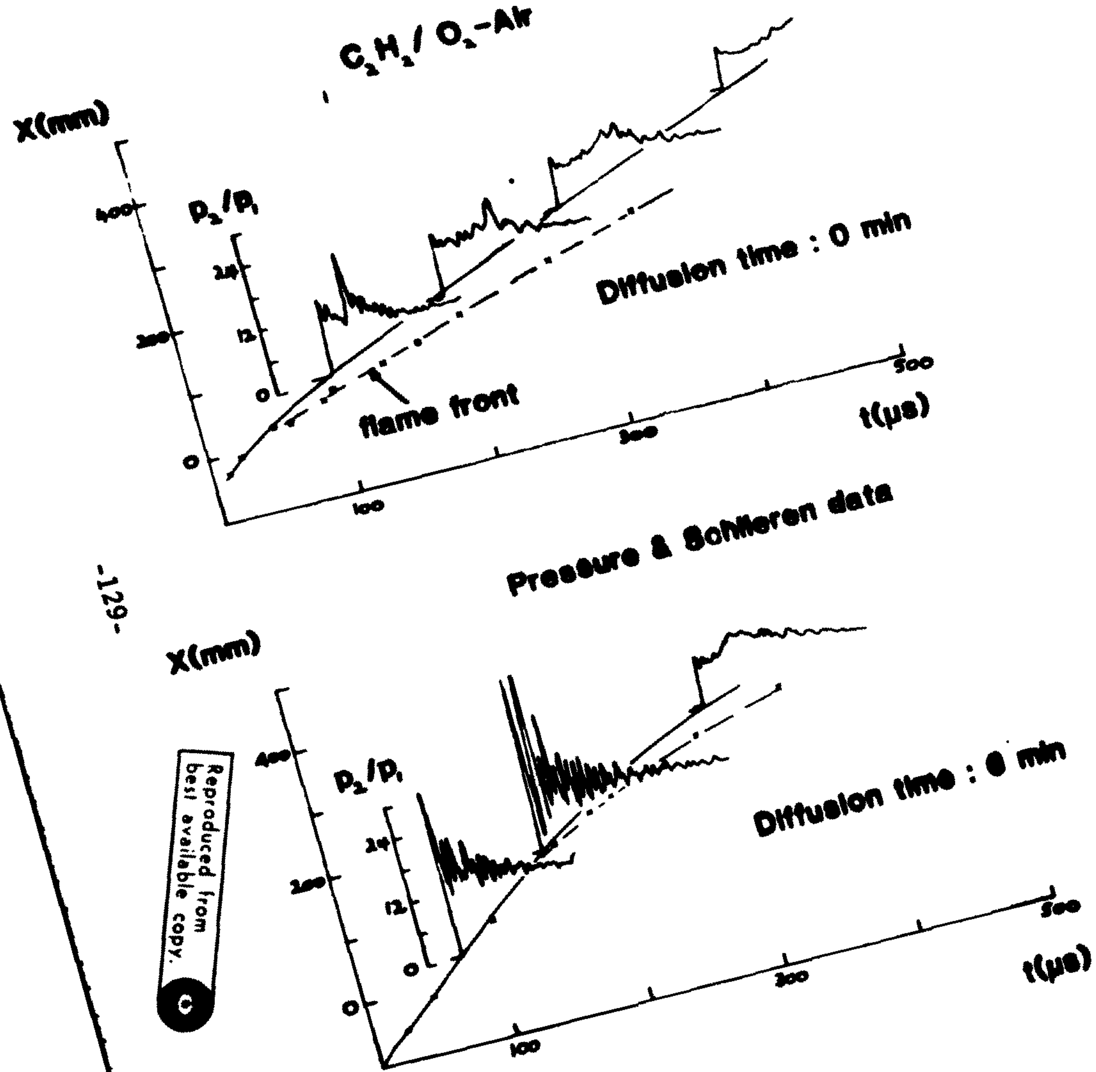
The simplest theoretical model for the refraction of a detonation wave at an interface with an inert gas assumes the detonation to be a square-wave of zero reaction thickness so that the post-shock state are the CJ values. The velocity of the transmitted wave calculated by such a model shows very poor agreement with observation: typically for a C_2H_2—O_2 detonation into He, Air, Ar and SF_6 exhibit discrepancies ranging from 60% to 75%. In view of the idealization of the model this is not surprising. In figure 1 some results are shown of the measured velocities of a detonation travelling from C_2H_2 - O_2 into argon for concentration gradients corresponding to diffusional times of 2, 4, 6 and 10 minutes. On the same diagram is shown the theoretical CJ values and also the measured velocities, at the appropriate dilutions, but in the absence of concentration gradients. The excellent agreement between the observed velocities with and without gradients indicates that in its transmission through a concentration gradient the wave adjusts very rapidly to the local compositional conditions. The discrepancy between the experimental and calculated values is entirely accounted for by tube-wall boundary-layer effects. Further evidence of the above conclusion was sought from smoked-foil records obtained in the region of diffusion.

Thus in figure 2 cell lengths are plotted as a function of distance from the slide for the indicated diffusion times. Also shown are the cell sizes measured in the same tube for steady waves at the corresponding dilutions. Although there is a fair amount of scatter the agreement confirms the conclusion from velocity data that the wave adjusts rapidly to the local conditions at all points in the concentration gradient.

Pressure profiles of a detonation in a concentration gradient with increasing inert dilutent exhibit a wide variation. Broadly speaking it is found that when the concentration gradient is steep a secondary pressure peak appears whereas for smaller gradients the wave exhibits pronounced oscillations. An example of these is shown in figure 2 in the case of C_2H_2 - O_2/air. These oscillations arise from transverse waves which rapidly increase in strength as the wave becomes marginal and when the reaction zone decouples from the front they decay in about 10 cell lengths. During this period the pressure oscillations will play an important role in any reignition process in an 'acceptor' mixture through which they are transmitted. At present no firm explanation can be offered for the secondary peaks that arise on decoupling in a sharp gradient. One possibility that suggests itself is some explosive mechanism similar to that found in 'galloping' waves. However no evidence has been found of a retonation wave upstream of the slide valve. It is more likely to be attributable to a wave interaction process between the shock and the detached flame front. On present evidence its role in the reignition of an acceptor is likely to be less important than those of the amplified transverse waves. The next phase of the work will seek answers to these questions in both confined and unconfined systems.

Established that :

- Cell size confirms that wave is CJ at all times
- Large concentration gradients : secondary shock
- Small concentration gradient : strong transverse wave



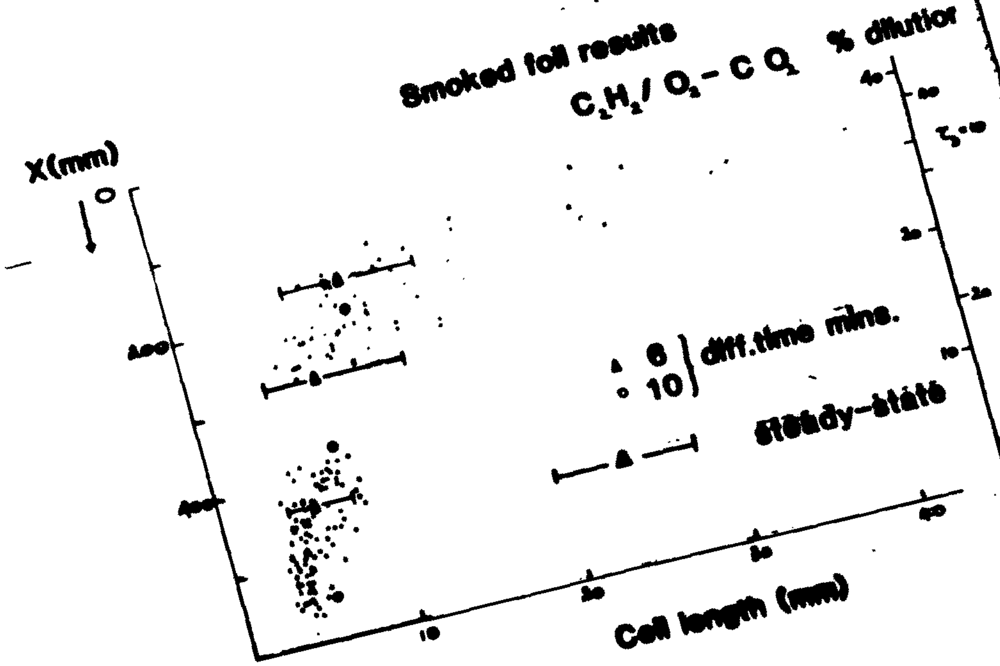


FIGURE 2

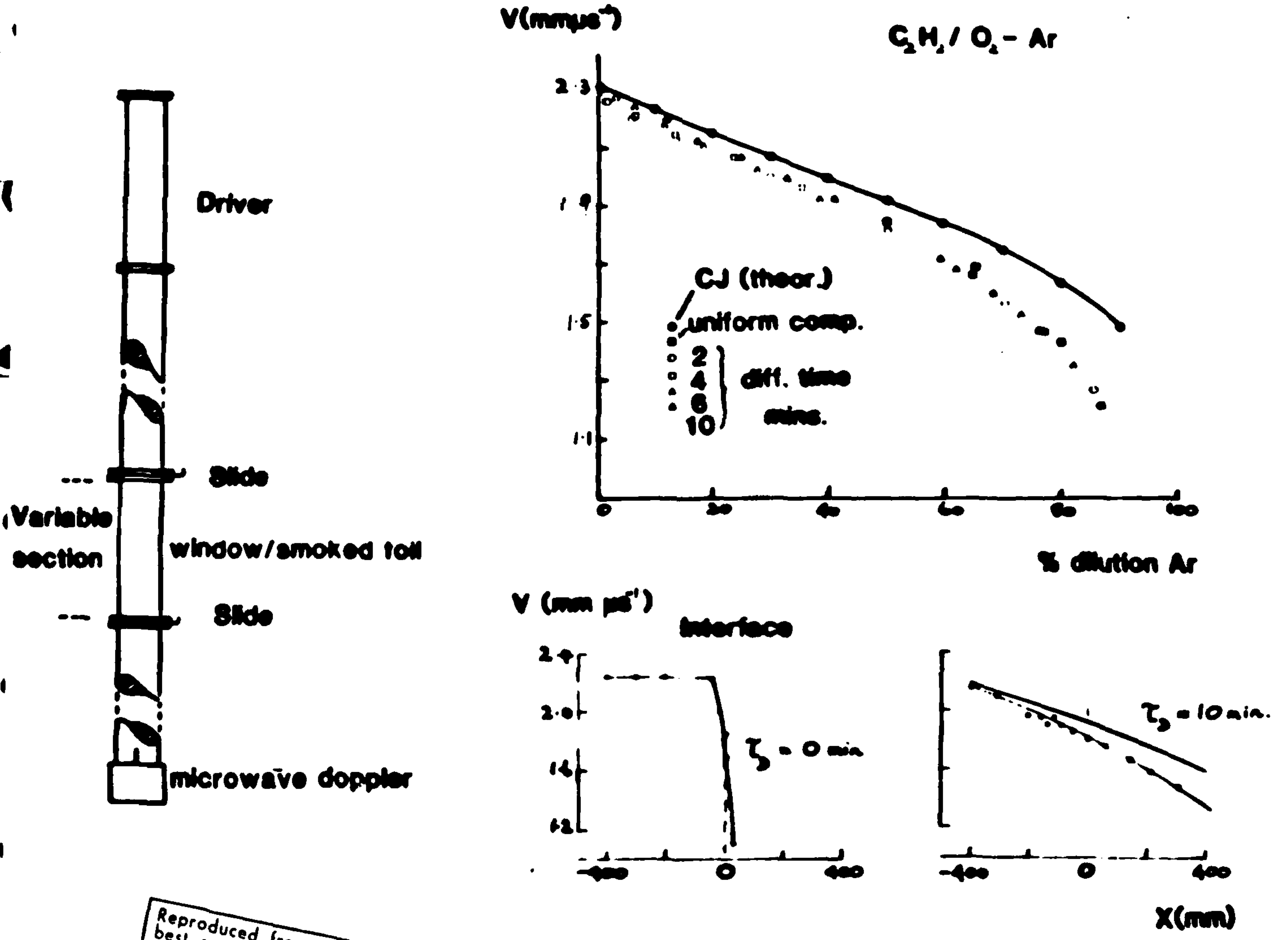
Reproduced from best available copy.

DETONATION WAVE BEHAVIOR AT CONCENTRATION GRADIENTS

APPROACH

- Vertical tube with slide valve to create diffusional gradient
- Study refraction of detonation at inert gas interfaces
- Establish properties of transmitted shock
- Study sympathetic ignition of acceptor using second valve
- Extend work to unconfined systems

FIGURE 1



Reproduced from best available copy.

TURBULENT COMBUSTION STRUCTURE USING TWO-POINT RAYLEIGH SCATTERING (F49620-80-C0065)

L. Talbot, M. Namazian and F. Robben*

Department of Mechanical Engineering
University of California
Berkeley, CA 94720

The overall purpose of this research program is to experimentally characterize the structure and fluid mechanics of turbulent combustion through detailed measurements of selected combustion configurations representative of real combustion systems and suitable for laboratory study. Laser based diagnostics for the fluid density (Rayleigh scattering), velocity (Laser Doppler Velocimetry) and high speed photographic visualization (particulate scattering and Schlieren) are used. In this past year a detailed study has been made at Lawrence Berkeley Laboratory, University of California, of a V-shaped, rod stabilized flame in a turbulent flow using two-point Rayleigh scattering. Information on the spatial length scales and evolution of the turbulent flame structure has been obtained. These results contribute towards an improved understanding of turbulent combustion processes leading to better numerical modelling in combustion systems of technical interest.

Our approach to this problem is demonstrated in Fig. 1. A premixed, V-shaped ethylene-air flame stabilized on a rod transverse to the flow (Fig. 1-A) has been studied using our recently developed two-point Rayleigh scattering technique (Fig. 1-B). This technique provides the simultaneous measurement of density at two points (points 1 and 2) in the flame. The two-point measurements were performed along the three x, y and z directions with the separation between the two points varied from 0 to 16 mm. The Single Beam System shown in Fig. 1-B was used when the separation between sampled points was in the horizontal direction (i.e., y and z). When the separation between the points was in the vertical direction the Dual Beam System was used. In this system the beam was split into green and blue beams and the distance between the focussed beams was varied by moving the upper half of a split lens as shown in Fig. 1-B.

One important question addressed by our research is whether the flame zone consists of a continuous wrinkled laminar flame which flactuates in position and shape (schematic shown in Fig. 2-A) or of ruptured pockets of flames, also called "flamelets" (schematic shown in Fig. 2-B). A clear answer to this question is very helpful for accurate modelling of turbulent flames and combustion systems.

*Lawrence Berkeley Laboratory, Berkeley, CA 94720

Our data show that, for the turbulent flames we have studied (equivalence ratio 0.6, flow velocity 7 m/sec and flame half angle 12°), they do not consist of "flamelets". This conclusion is drawn from inspection of the joint probability density function (jpdf) for the two-point density measurements as shown in Fig. 2-C. Here the two sampled points are separated by 1.2 mm across the flame. The inset in the figure shows the relative position of the sampled points with respect to the turbulent flame zone.

Since the laminar flame thickness (about 0.5 mm) is considerably smaller than the turbulent flame zone (about 4 mm), the jpdf of the densities primarily shows the probability of either burned or unburned mixtures at the points of measurement. The jpdf shown has three peaks, labeled α, β and γ, each which could be due to a relative position of the fluctuating thin flame with respect to the two sampled points shown schematically in Fig. 2-A. When the flame sheet is positioned along the contour labelled α in Fig. 2-A, then the measurement points labelled 1 and 2 result in the peak labelled α in Fig. 2-C. Similarly, when the flame sheet is positioned on contour β the peak labelled β is obtained, and when the flame sheet is positioned on the contour γ the peak labelled γ is obtained.

If there were flamelets in this flame, as shown schematically in Fig. 2-B, then with a random distribution of these flamelets there would be a fourth peak in the jpdf, corresponding to burned mixture for point 1 and unburned mixture for point 2. Since there is no measurable probability for this situation as shown in Fig. 2-C, we conclude that there are no flamelets in the present flame.

Further analysis of our data reveals that the present flame's density fluctuation structures have the same integral length scale of 2 mm in all three directions. It was also found that these structures are convected downstream at the flow velocity.

Application of the two-point Rayleigh scattering to different flames and at different conditions is in progress. We expect to be able to extend and generalize our conclusions on turbulent flame structure.

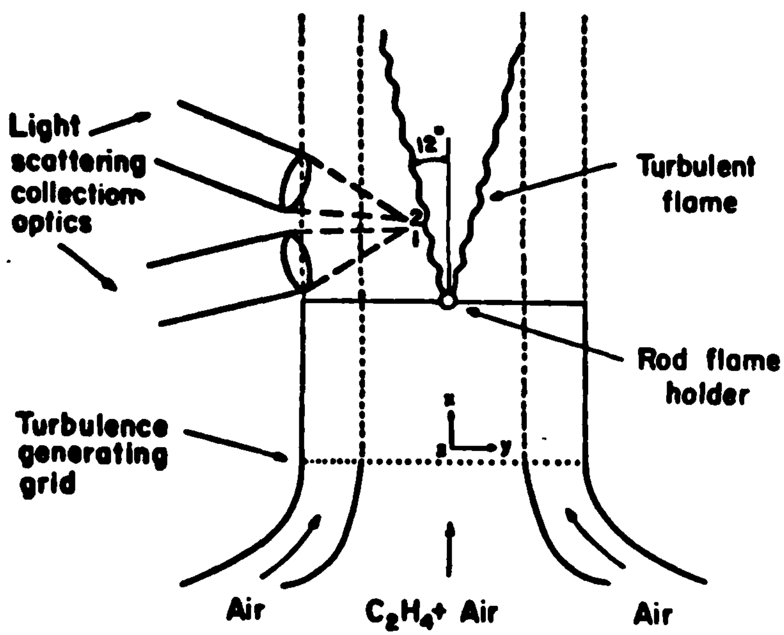
Air Force Basic Research

TURBULENT COMBUSTION STRUCTURE

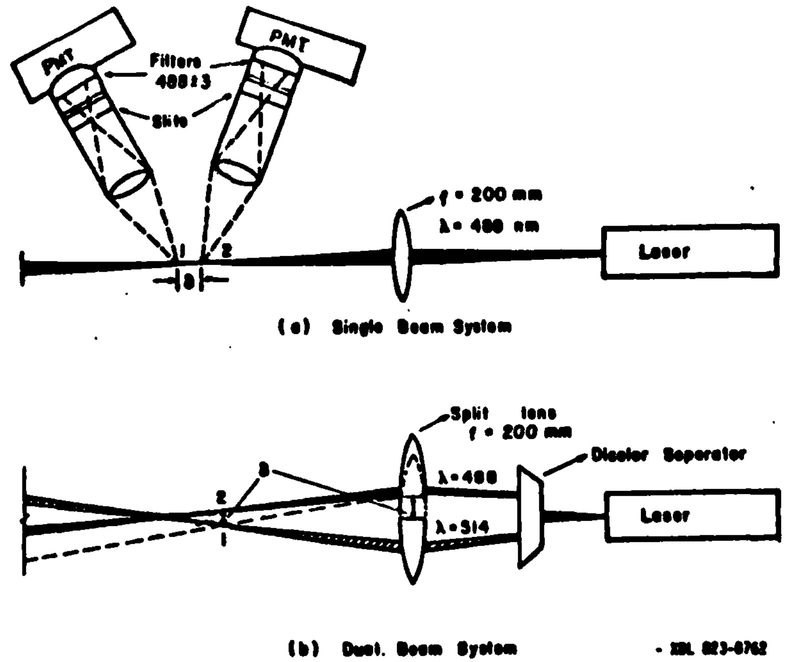
APPROACH

Two-point Density Measurement by Rayleigh Scattering Technique

* Information on flame structure
* Associated length scales
* Experimental Input for modeling
* New diagnostics tool



Turbulent flame configuration for Two-point density measurement
(1-A)



Optical configuration for Two-point density measurement by Rayleigh Scattering
(1-B)

Talbot/Namazian/Robben
UCB

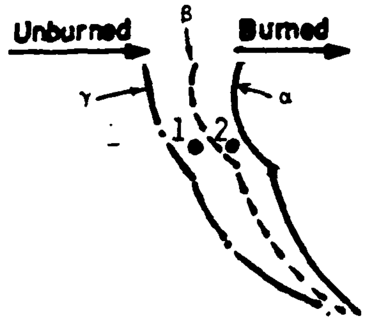
Air Force Basic Research
Achievement

TWO-POINT RAYLEIGH SCATTERING

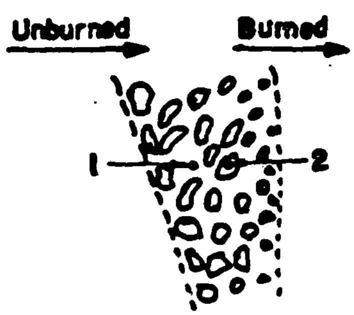
JPDF HAS 3 PEAKS WHICH CAN BE EXPLAINED BY "WRINKLED LAMINAR FLAME" MODEL

BUT NOT BY

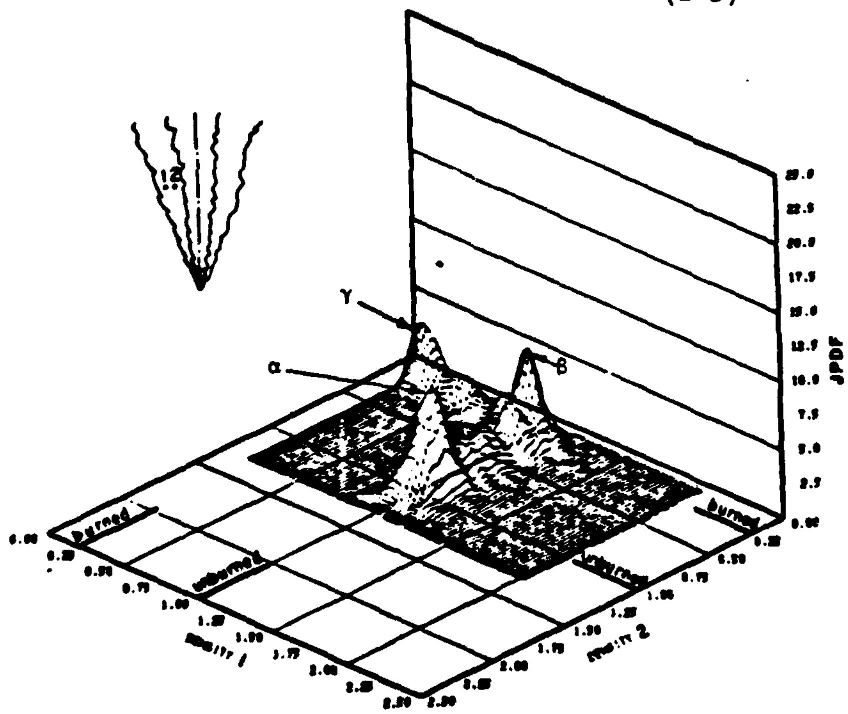
"FLAMELETS" MODEL



"WRINKLED LAMINAR FLAME" MODEL
(2-A)



"FLAMELETS" MODEL
(2-B)



JOINT PROBABILITY DENSITY FUNCTION OF TWO-POINT RAYLEIGH SIGNAL
(2-C)

Talbot/Namazian/Robben
UCB

TURBULENT COMBUSTION STRUCTURE

DESCRIPTION OF VU-GRAPHS

Approach

Fig. 1-A: Turbulent flame configuration for two-point density measurement

The experimental burner is an open jet design with the fuel-air mixture surrounded by a co-flowing air stream of the same velocity. We are able to produce the important characteristics of turbulent flame propagation in this apparatus.

Fig. 1-B: Optical configuration for two-point density measurement by Rayleigh scattering

This shows the two methods for making simultaneous measurements of the density of the combustor shown in Fig. 1-A. The single beam system was used when the separation between two sampled points was in the horizontal (y and z) directions. The dual beam system was used when the separation was in vertical (x) direction for which it was impractical to bring the laser beam vertically downward. In the dual beam system the laser beam was separated into a blue and a green beam and the distance between the sampled points was varied by moving the upper half of a split lens away from the lower half.

TURBULENT FLAME STRUCTURE

Achievement

Fig. 2-A: "Wrinkled Laminar Flame" model

This figure schematically shows a wrinkled laminar flame. According to this model the flame zone (or flame brush) consists of a thin flame sheet which fluctuates in shape (wrinkled) and in position. In this schematic α, β and γ indicate the three positions of the wrinkled flame sheet with respect to the two sampled points, labelled 1 and 2.

Fig. 2-B: "Flamelets" model

According to this model the flame zone consists of raptured fire balls known as flamelets.

Fig. 2-C: Joint probability density function of two-point Rayleigh signal

This shows the jpdf for the two-point density measurements when the two points are separated by 1.2 mm in the direction across the flame. The inset in the figure shows the relative positions of the sampled points with respect to the flame brush. Note that the density axes are normalized by the unburned gas density. The three peaks in this jpdf are labelled by α, β and γ which correspond to the three relative positions of the instantaneous flame and the measurement points indicated in Fig. 2-A.

Talbot/Namazian/Robben
UCB

Interfacial Chemical Reactions and Transport Phenomena in Flow Systems

Principal Investigator: Daniel E. Rosner
High Temperature Chemical Reaction Engineering Laboratory
Yale University, New Haven CT, 06520 USA
Contract: F49620-82K-0020

EXTENDED ABSTRACT+

1. Technical Objectives

The performance of existing and proposed air-breathing chemical propulsion systems is often limited by rate processes occurring at or near phase boundaries-as in the fouling/corrosion of gas turbine (GT) blades and heat exchanger tubes, soot burnout or deposition on GT combustor flame tubes, the determination of volumetric heat release rate in liquid and/or slurry fuel combustors, catalyst deactivation in surface-catalyzed combustors, etc. Accordingly, this research program is directed toward providing systems and materials engineers with a quantitative understanding of important interfacial rate processes, both for gas/solid and gas/liquid interactions, with emphasis on high temperature systems.

2. Approach

An interactive experimental-theoretical approach is being used to develop rational engineering correlations of performance-limiting chemical, and energy/mass transfer phenomena at interfaces. This includes the development and exploitation of laboratory flat flame burners and flow-reactors, along with the necessary diagnostic techniques. Resulting experimental data, together with the predictions of comprehensive asymptotic theories, are then used as the basis for establishing and testing simple view-points and engineering correlations.

3. Research in Progress

Presently, we are investigating the following interfacial rate processes:

3.1 Surface-catalyzed combustion of light (H_2) and heavy (hydrocarbon) vapor fuels in both forced and natural convection reactors (with emphasis on the consequences of Soret mass transport).

+ AFOSR Contractors Meeting on Air Breathing Combustion and Explosion Research, November 1-4, 1982; Clearwater Beach, Fla.

3.2 Submicron particle deposition from flat hydrocarbon/air flames[1], (with emphasis on the development of optical techniques and the role of thermophoresis in augmenting deposition rates).

3.3 Theory of thermophoretically enhanced diffusive-convective transport of particles across laminar or turbulent non-isothermal boundary layers[2-6].

3.4 Theory of inertially modified particle dynamics and capture in forced-convection systems[3,4,6,7].

3.5 Theory of the evolution of deposits on bodies of arbitrary shape[8].

4. Selected Results

Ongoing results are fully discussed and documented in the references cited in Section 6⁺. A particularly interesting and representative outcome of our research, Fig. 1, shows the test of our recently developed correlation

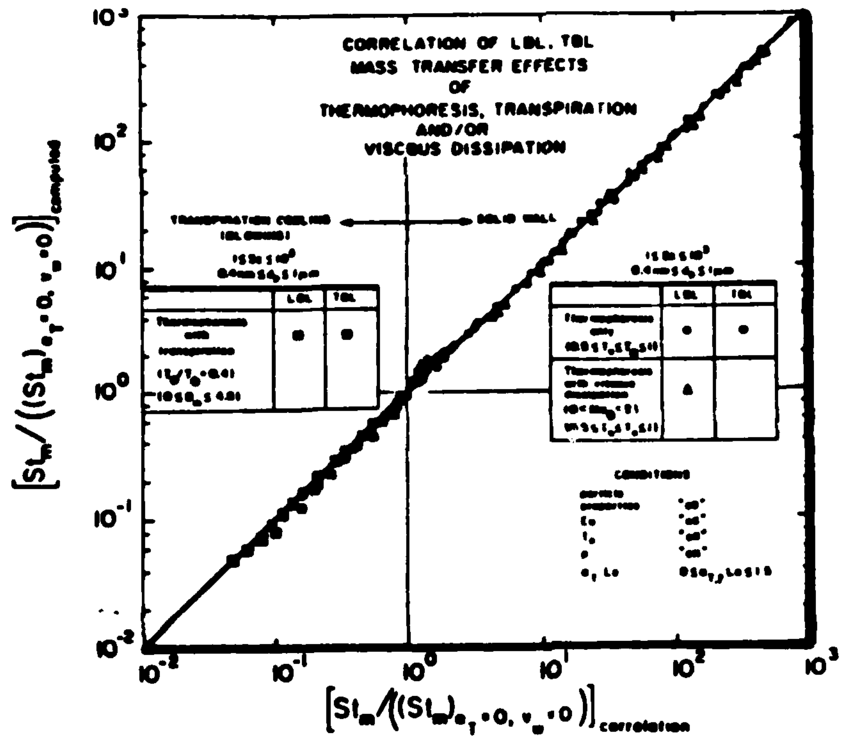


FIG. 1 Test of Thermophoretic "Suction" - Thermophoretic "Sink" Correlation Scheme (Section 4) Against Exact Solutions to the Particle Mass Conservation Equation for Self-Similar Laminar Boundary Layers (after Gokoḡlu and Rosner (1982)), and Law-of-the-Wall Fully Developed Turbulent Boundary Layers.

⁺ Copies of these preprints or reprints are available via D.E.R.

for rapidly predicting particle mass transport rates across laminar or turbulent non-isothermal boundary layers, including transpiration cooling or viscous dissipation effects. The quantity plotted is the ratio of the actual mass transfer coefficient (Stanton number) to the corresponding coefficient in the absence of particle thermophoresis. Over 100 points have been examined to date, with our correlation exhibiting an average error less than 8 pct. over the parameter range investigated ($0.5 \leq T_w/T_e \leq 1.0$, $0 \leq$ Mach no. ≤ 2, $10^0 \leq$ Schmidt no. $\leq 10^6$).

5. Plans

Our present plans include moving into the following ancillary areas:

5.1 Theory of transport and reaction for non-spherical particles (eg. combustion-generated agglomerates, such as soot).

5.2 Soot deposition experiments using rich, premixed flat flames; exploration of implications for combustor wall/turbine blade soot deposition, and soot sampling from laboratory combustors.

5.3 Theory of shape and topography of combustion-derived deposits, and the parameters (eg. particle sticking coefficient) that influence them.

5.4 Effects of advanced air-cooling-techniques (film and transpiration) on particle deposition from combustion gases.

6. References

1) Atkins, R. and Rosner, D.E., "Experimental Studies of Salt/Ash Deposition Rates from Combustion Products Using Optical Techniques", Proc. Int. Conference on Experimental Research into Fouling and Slagging Due to Impurities in Combustion Gases (R. Bryers, Ed.), Engineering Foundation, New York (in press, 1982).

2) Rosner, D.E., Gokoglu, S. and Israel, R., "Rational Engineering Correlations of Diffusional and Inertial Particle Deposition Behavior in Non-isothermal Forced Convection Environments", Proc. Int. Conference in Fouling of Heat Exchange Surfaces (R. Bryers, ed.), Engineering Foundation, New York (in press, 1982).

3) Rosner, D.E. and Fernandez de la Mora, J., "Correlation and Prediction of Thermophoretic and Inertial Effects on Particle Deposition from Non-Isothermal Turbulent Boundary Layers", in Particle-Laden Flows in Turbomachinery, ASME, New York, 1982.

4) Fernandez de la Mora, J. and Rosner, D.E., "Inertial Deposition of Particles Revisited and Extended: Eulerian Approach to a Traditionally Lagrangian Problem", Physico-chemical Hydrodynamics 2, 1-21 (1981).

5) Rosner, D.E. and Fernandez de la Mora, J., "Small Particle Transport Across Turbulent Non-Isothermal Boundary Layers", ASME Transactions - J. Eng. for Power (in press, 1982).

6) Fernandez de la Mora, J. and Rosner, D.E., "Effects of Inertia on the Diffusional Deposition of Particles to Spheres and Cylinders at Low Reynolds' Numbers", J. Fluid Mechanics (in press, 1982).

7) Israel, R. and Rosner, D.E., "Use of a Generalized Stokes Number to Determine the Aerodynamic Capture Efficiency of Non-Stokesian Particles from a Compressible Gas Flow", Aerosol Science and Technology (in press, 1982).

8) Rosner, D.E., Gunes, D., Anous, N., "Aerodynamically-Driven Condensate Layer Thickness Distributions on Isothermal Cylindrical Surfaces", Chemical Engineering Communications (submitted July 1982).

AIRBREATHING PROPULSION RESEARCH AT TECHNION

A. Gany
Technion University - Israel

ABSTRACT NOT AVAILABLE

TRANSIENT COMBUSTION DYNAMICS, FUEL DROPLET DECOMPOSITION AND BREAKUP

AFOSR GRANT 82-0222

MELVIN GERSTEIN AND P. ROY CHOUDHURY

Mechanical Engineering Department
University of Southern California
Los Angeles, California 90089-1453

There are three major objectives of this program. The first objective is to determine the effect of coupled evaporation and liquid phase decomposition occurring simultaneously in a spray of a liquid fuel at higher pressures typical of an advanced air-breathing propulsion system. The second objective is to explore a novel method of shattering a droplet of a slurry fuel by means of irradiation at selected frequency bands. The third objective of this program is to investigate the fundamental causes of combustion instability induced by pressure oscillations in the inlet of a propulsion system. The effectiveness of a feed back control system in smoothing out rough burning and combustion instability is to be investigated as a part of the third objective.

Analytical studies of coupled evaporation and decomposition of a spray show that the thermal interaction between the spray and the ambient gas stream is extremely important and should not be disregarded. The cooling of the ambient stream due to the evaporation of fuel changes the system behavior and the distribution function drastically. It also delays the formation of insoluble residue species. Figure 1a shows the comparison of the overall equivalence ratio between the variable and constant ambient temperature cases. Figure 1b shows the distribution functions where the entire spray reduces to a distribution of residue particles for a different frequency factor.

Slurry fuel droplet are shattered by means of irradiation at selected frequency bands where the solid part of the slurry acts as black body and the liquid does not absorb any radiation. Figures 2a and 2b show shattering of ARCO Graphite oil by means of a 20 mJ laser beam with a pulse duration of 15 nanosec. Analysis shows that a minimum pulse duration of a microsec will be necessary to shatter the droplet thermally.

Analytical solution of the boundary layer in a channel flow with a pulsing pressure shows that the boundary layer flow separates and reattaches periodically. This reattachment and separation of flow at the dump station is believed to be the cause of the combustion instability induced by the oscillation of the inlet pressure. The concept of feedback loop will enable one to bleed gases in the boundary layer to prevent flow separation and shedding of vortices at the critical frequency. Figure 3 shows the concept of feedback system for counteracting the combustion instability induced by the oscillation of the inlet pressure.

In the future both analytical and experimental work will continue to understand the fundamental mechanisms involved in all of the three major objectives of the grant.

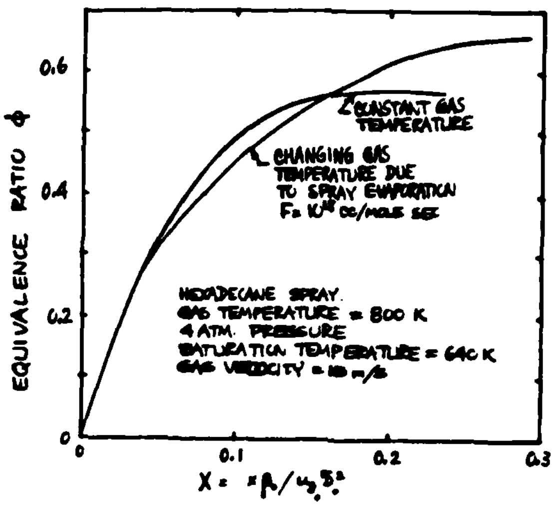


FIGURE 1a EFFECT OF VARIABLE AMBIENT TEMPERATURE

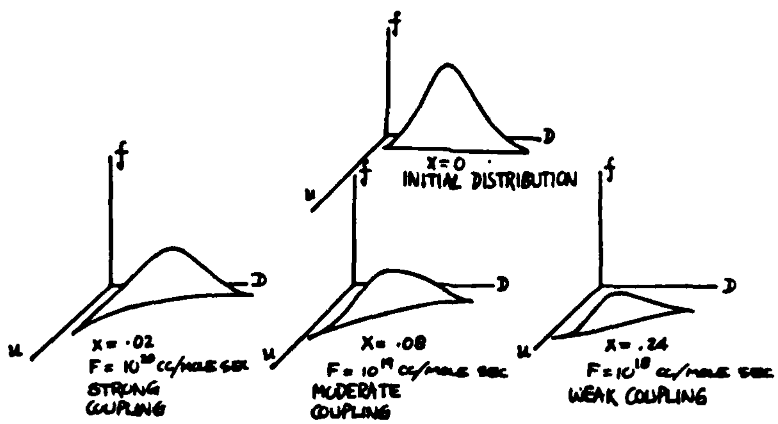


FIGURE 1b $f(u,D,x)$ AT THE POINT OF ALL RESIDUE PARTICLES. DIFFERENT DECOMPOSITION RATES. HEXADECANE SPRAY.

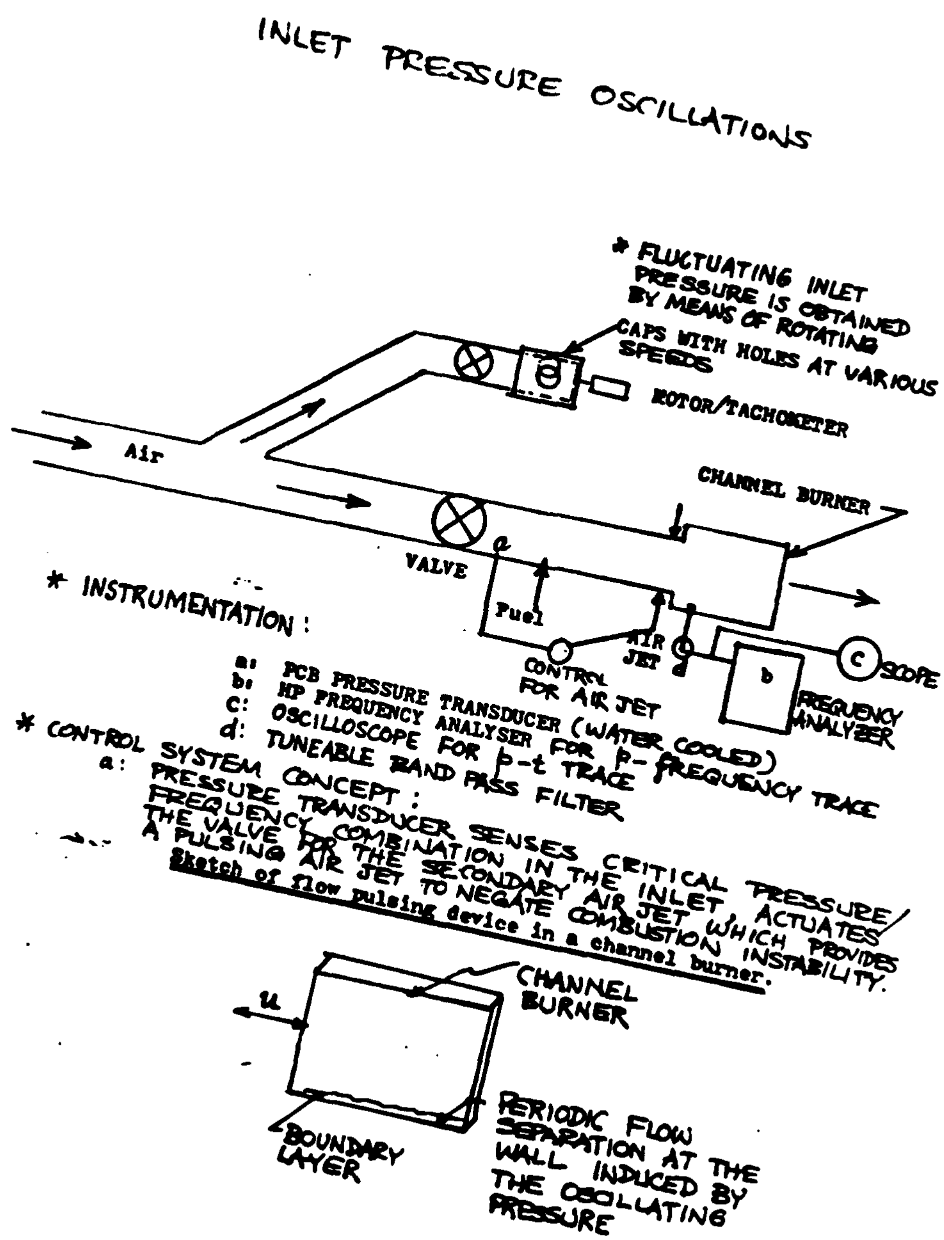
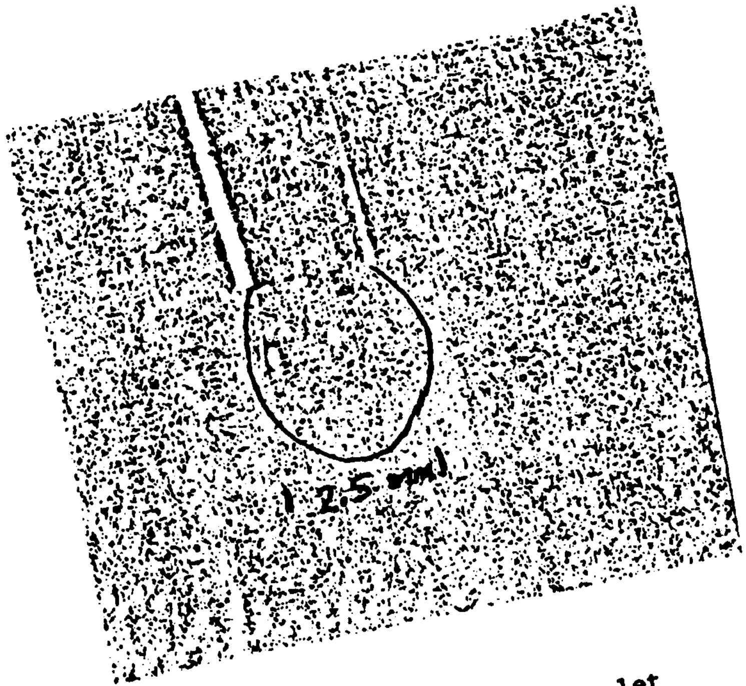


Figure 3. Combustion Oscillation and Feedback Control Concept.



2a Original Slurry Droplet

2b Traces of Shattered Drop

A PROPOSED INVESTIGATION OF SPRAY VAPORIZATION AND COMBUSTION IN A RECIRCULATING FLOW

T.R.Troutt, J.N.Chung and S. Wojcicki
Mechanical Engineering Department
Washington State University

Abstract

Recent experimental evidence indicates that organized turbulent structures are of dominant importance in the vaporization and combustion of liquid sprays within free shear flows. An adequate knowledge of the mechanics and development of flows of this type is essential for understanding two-phase spray dispersal and flame stabilization within gas combustors. Presently, however, more information is needed to develop a detailed description of the dynamical interaction between the droplets and the turbulent structures. The major objective of the proposed study is to use advanced experimental and numerical analyses to provide this description.

The flow field to be studied will be a separated shear flow created by the motion of a uniform air stream over a two-dimensional downstream facing step. Both burning and non-burning flow field conditions will be studied. This flow incorporates many of the essential properties of typical recirculating flows in gas combustors with a minimum of geometrical complexity.

The experimental measurements will employ laser velocimetry for the gas velocity measurements. Droplet sizing and velocity information will be obtained using high speed photographic methods and a Doppler-Mie combination laser optic technique. The numerical analysis will use a discrete vortex method to directly simulate the flow field. Droplet trajectories and vaporization rates will then be computed from the simulated flow using a momentum coupling technique. Interpretations developed from the combined analyses will be used to identify and quantify the controlling phenomena.

RESEARCH AT LLL ON ADVANCED DIAGNOSTIC TECHNIQUES AND AIRBREATHING COMBUSTION DYNAMICS RELATED PHENOMENA

D.L. Hartley

Sandia-Lawrence Livermore Laboratories

ABSTRACT NOT AVAILABLE

STUDIES OF COMBUSTION PROCESSES IN THE APL COMBUSTION RESEARCH FACILITY

W. M. Roquemore, R. P. Bradley, J. S. Stutrud, C. M. Reeves and R. L. Britton

Air Force Wright Aeronautical Labs
Aero Propulsion Laboratory
Wright Patterson Air Force Base, Ohio 45433

The research combustor illustrated in Figure 1 was developed for the purposes of evaluating diagnostic techniques and performing experiments to aid in the development of combustion models. During preliminary evaluations of this combustor, high speed movies of the flame revealed an unsteady flame behavior in the near-wake, recirculation region [1] at conditions far removed from blow-off. This complicated motion appeared to result in the formation of discrete packets of flame downstream of the recirculation zone. These flame packets referred to as flame turbules are clearly evident in Figure 2. The objective of this year's research has been to characterize the dynamic behavior of the flame turbules to determine how they are formed and to determine their importance to the combustion processes.

The two spectrophotometer set-up shown in Figure 1 was used to make time resolved CH optical emissions measurements as the flame turbules passed by their field of view [2]. The velocity, frequency and time widths of the flame turbules were determined from these measurements for different air and fuel flow rates and at different axial distances downstream. The fraction of time or the probability that a flame turbule is present at a given axial location was also calculated. A correlation was established between the time averaged centerline temperatures at different axial locations downstream of the recirculation zone and the probability that a flame turbule was present. The result that the time averaged temperatures are due to the flame turbules and nonreacting regions passing by the probe illustrates the inadequacy of using time averaged measurements to deduce the fundamental physics of unsteady combusting flows.

An LDA system has been used to make simultaneous velocity and flame emissions measurements in the APL combustor at an axial location where the flame turbules are well defined [3]. The results of using the flame emissions to conditionally sample the velocity measurements corresponding to flame (luminous) and no flame (nonluminous) conditions are shown in Figure 3. The positive skewed velocity distribution obtained using all the velocity data are shown to be the result of two distinctly different distributions, one associated with the flame turbules and the other with the nonluminous regions.

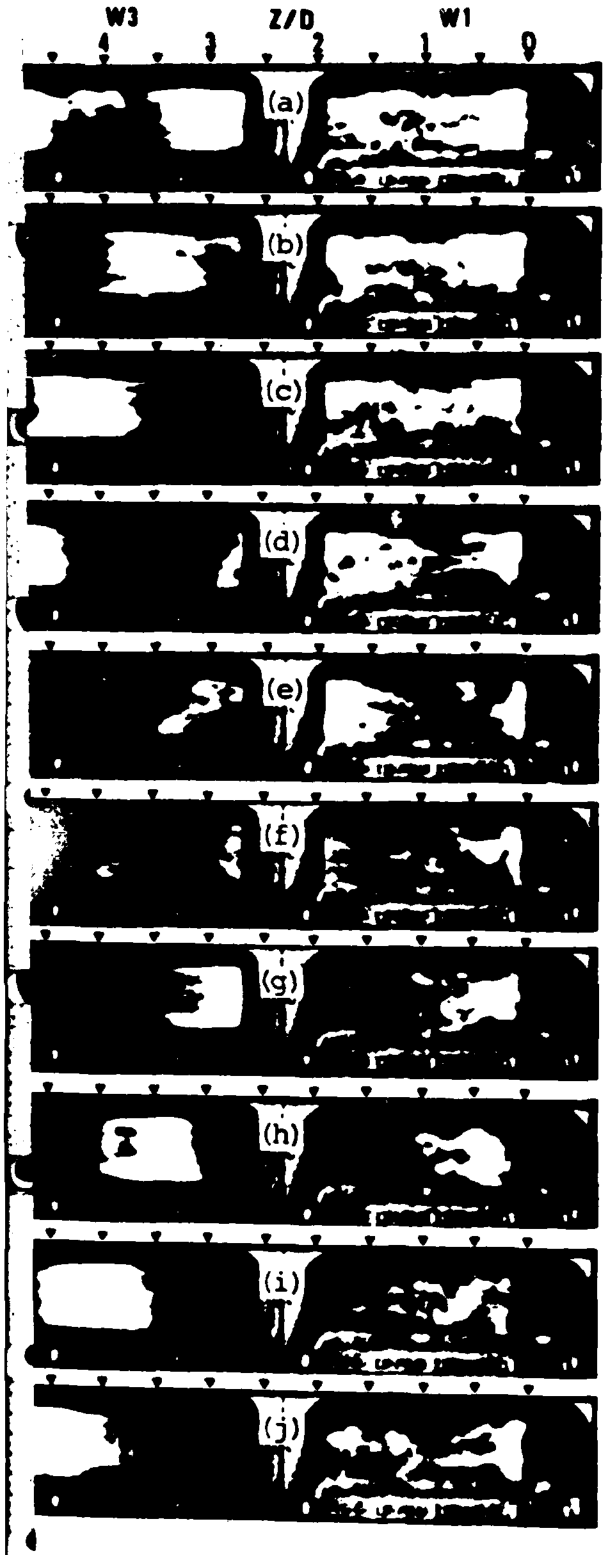
An unexpected result of the velocity/flame emissions measurements was the recognition that the time averaged LDA data can be in considerable error in unsteady flows where combustion and nonreacting combustion regions pass separately through the measurement location. The flame turbules were estimated to be present 74% of the time based on an analysis of the continuous time record of the emissions. This implies that the luminous peak in Figure 3 should be considerably larger than the nonluminous peak. Because this is contrary to the observed result, it is believed that a bias occurred in the LDA measurements as a result of the seed density being lower in the combusting regions than in the nonreacting regions. The difference in seed density is believed to occur because of a large difference in temperature between the two regions.

The question arises about whether practical combustion flows, such as those in gas turbine combustors or afterburners, exhibit similar discrete flame structure behavior. Figure 4 illustrates the similarity between the time resolved optical emissions measurements made in the APL centerbody, the time resolved reaction product measurements made behind a splitter plate [4] and the temperature measurements made in a gas turbine combustor [5]. The splitter plate experiments show that the peaking of the product concentration in time is the result of the mixing occurring within large scale structures. The similarities of the time traces suggest that large scale structures may be important to the mixing processes occurring in the APL combustor. Recent high speed movies also show that vortices are shed from the face of the APL combustor. The interaction of the shed vortices with the reverse flowing fuel and air mixture in the recirculation zone is believed to be one of the mechanisms responsible for the formation of the flame turbules. The shed vortices also appear to be important in the mass and heat transport between the annular air stream and the recirculation zone. Based on these results, the authors suggest that shed vortices may be important to the *flame holding characteristics* of bluff-body stabilizer such as those used in afterburners.

References

1. Roquemore, W. M. et al, ASME Publication 80-Gt-93, Mar 80
2. Roquemore, W. M. et al, AIAA-82-1078, Jan 82
3. Magill, P. D., et al, AIAA-82-0883, Jun 82
4. Breidnethal, R., J. Fluid Mech. Vol 107, pp1-24, 1981
5. Dils, R. R., J. Eng, Power Trans. ASME Series A, 95 No. 3, p 265, 1972

Figure 1. Schematic of APL combustion tunnel and optical emissions system



2 Photographs (2ms apart) showing the presents of the flame turbule as observed through Windows W_1 and W_3 in Figure 1.

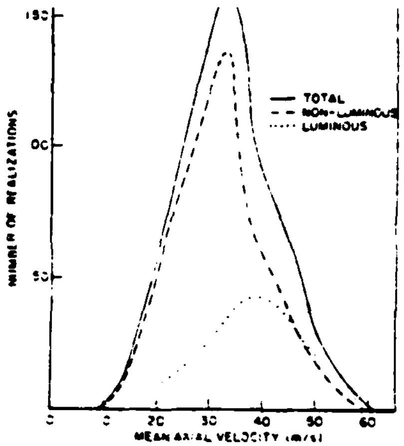


FIGURE 3 Distribution of the axial velocity component using flame emissions to conditionally sample the LDA data.

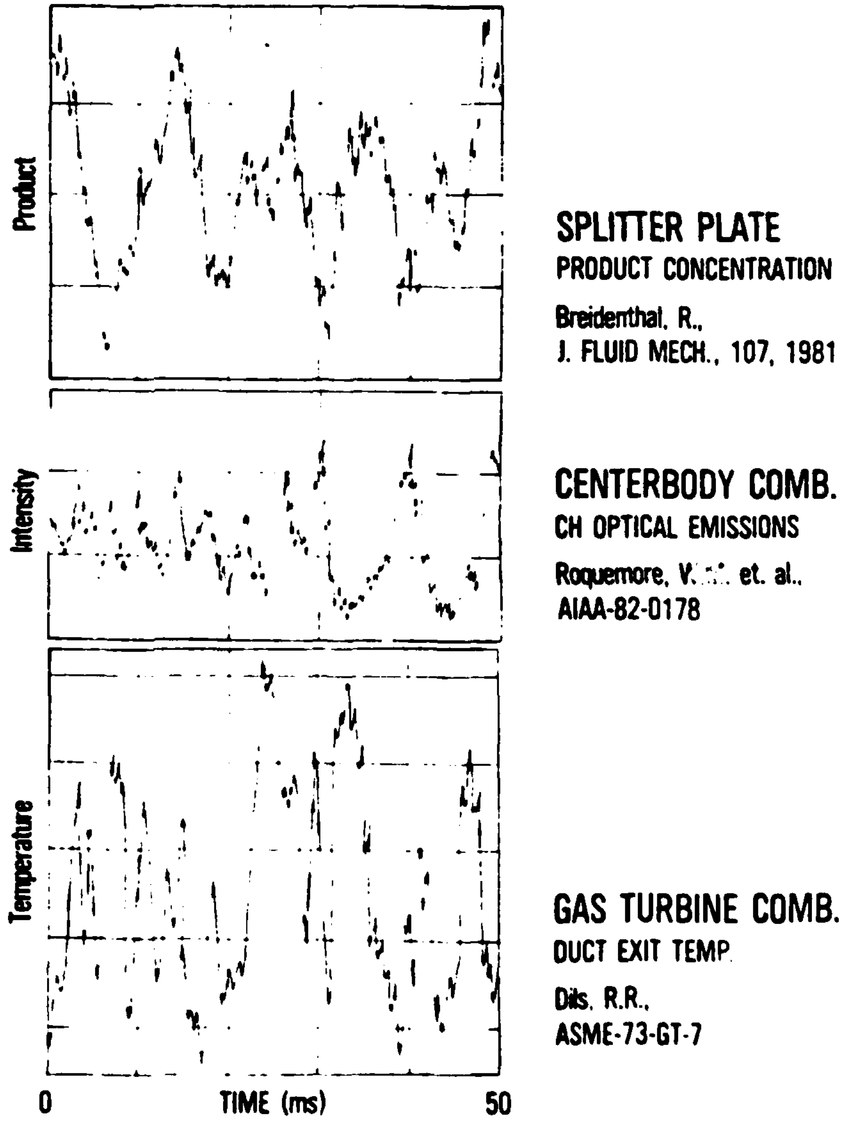


FIGURE 4 Time records for three reacting flow configurations.

TIME AND SPACE RESOLVED INSTANTANEOUS
MEASUREMENT OF VELOCITY VALUES

Holger T. Sommer

Department of Mechanical Engineering
Carnegie-Mellon University
Pittsburgh, PA 15213

GRANT AFOSR 82-0266

ABSTRACT:

A wide range of flows of interest in science and engineering can be investigated by applying laser-doppler velocimetry (LDV). In its current configuration the LDV method is used to measure flow velocities and velocity distributions by recording the doppler shift of light scattered by particles in the flow of interest. However, some flows of interest exist, where the LDV-method does not produce satisfactory results in connection with existing signal analyzing systems. (Internal combustion engine, high turbulent flow). Current electronic data acquisition systems such as counter, tracker and digital correlator fail to analyze and process LDV signals generated by high turbulent flows and flows with fast changing velocity directions. Because wide band LDV acquisition systems are restricted to certain types of signals, their application in difficult flow situations is questionable. In order to overcome this problem associated with processing noisy LDV signals from instationary high turbulent flows, an optical spectrum analyzing method will be applied.

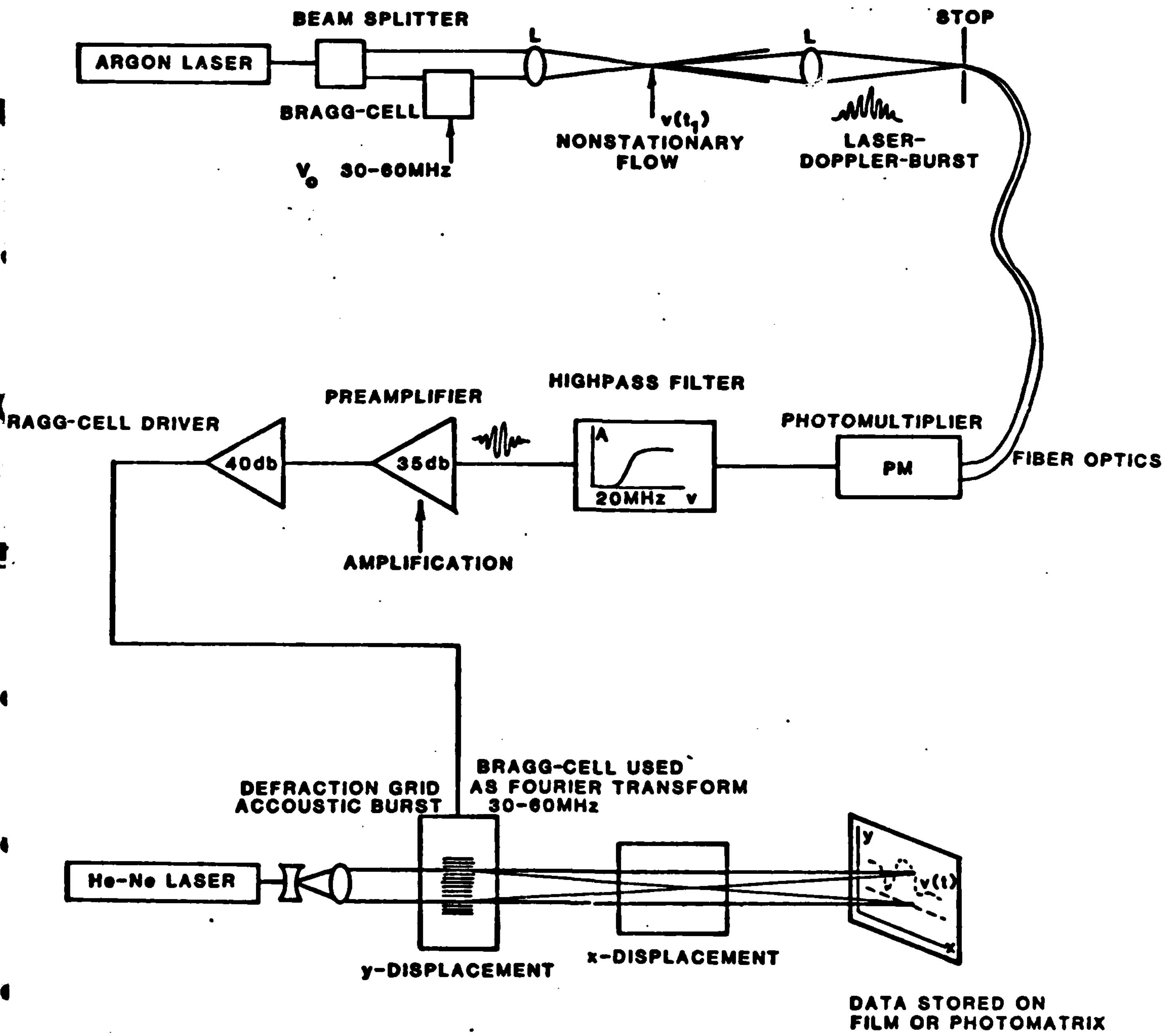
In addition to these requirements, the decoupling of the signal processing procedure from the form of the signal and the seeding density is of interest to extract the useful information related to the physics of the observed flow. The optimal solution of the above mentioned problems is produced by fast fourier-transform-techniques of the signals of interest. Using electronic frequency analyzers, the time necessary to process the signal is too long compared with the overall "LDV-Burst" time. Using optoelectronic fourier-transform by applying the optoaccoustic effect of a bragg-cell it will be possible to produce real time spectra of about 30 MHZ bandwidth at a mean-frequency of about 40 MHZ. A schematic of the optoelectronic signal-processing system is given in the Figure.

The LDV-Burst received by the photomultiplier is high-pass filtered and amplified up to a power level of about 1-2 watt. This signal is used to generate an ultrasonic burst in the optical part of a bragg-cell. Laser light is defracted at the generated sonic wave-pattern and the angle of defraction is a function of the frequency feed into the bragg-cell. The intensity of the defracted laser beam (1. order of defraction) is a maximum if the laser beam is entering the cell under bragg-conditions. The displacement of the first order of defraction of the laser beam is directly proportional to the frequency, and can be stored photographically.

PROJECT STATUS:

The project was started with a detailed familiarization and literature review of design criteria for optoaccoustic and electronic instrumentation. Bragg-cells of different vendors have been evaluated and components to build an optical spectrum analyzer are on order. Since the project is in its early state, measurements and a performance demonstration cannot be given at present.

SYSTEM FOR VELOCITY MEASUREMENT AND INSTANTANEOUS FREQUENCY ANALYSIS.



HIGH TEMPERATURE CATALYTICALLY ASSISTED COMBUSTION (AFOSR-81-0248)

F.V. Bracco, B.S.H. Royce and D.A. Santavicca
Department of Mechanical and Aerospace Engineering
Princeton University, Princeton, N.J. 08544

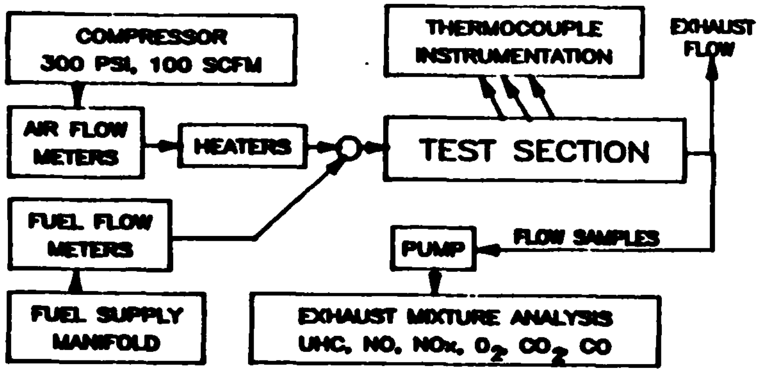
The catalytic combustion research program at Princeton is a combined theoretical and experimental investigation of the basic fluid dynamic, physical and chemical processes in catalytic combustion associated with air breathing propulsion systems. The objective being an assessment of the relative importance of gas phase kinetics, heat transfer, mass diffusion and surface chemical kinetics from which more realistic analytical representations of these processes can be developed.

Experiments are conducted in a steady combustor facility, shown schematically in Figure 1, over a range of typical afterburner conditions. Measurements of substrate temperature profiles and exhaust gas temperature and composition profiles are made. The results of the experiments provide a data base that is used in the development and testing of numerical models of the catalytic combustion process. A major recent accomplishment is the development of a two-dimensional transient model which includes coupling between the gas and substrate as well as radiative heat loss to the outside, providing solutions for the two-dimensional temperature field in the gas and the substrate (Figure 1). The model has been used to predict the transient and steady state behavior of CO/Air mixtures in a catalytic honeycomb. In the calculation the inlet conditions for velocity and temperature are set and the transient begins by injecting fuel. Results comparing the predicted and measured steady state substrate temperature profile are shown in Figure 2 along with the imposed fuel transient and the steady state inlet conditions.

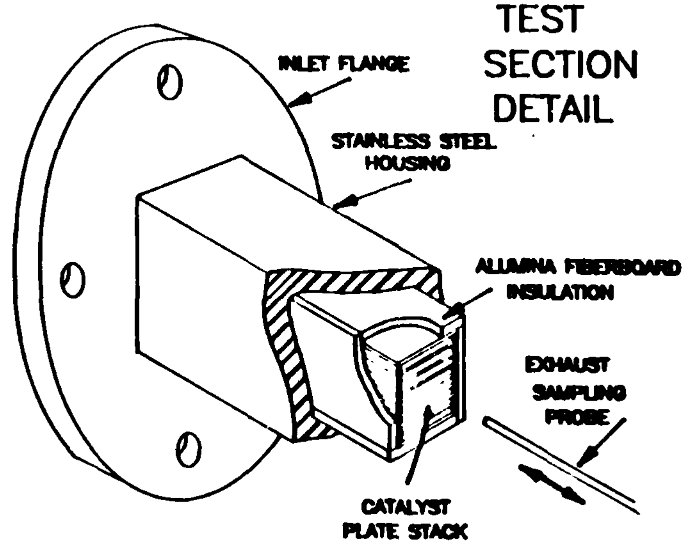
An additional interest of the catalytic combustion program at Princeton is in the area of catalyst development, where the ideal catalyst would exhibit both low temperature light off and high temperature durability. A new catalyst has been designed to exhibit long lifetime at high temperatures and adequate ignition characteristics at low temperatures. The catalyst is a modified perovskite based on $La(Cr_{0.5}Al_{0.5})O_3$. This ceramic has been doped to make it electrically conductive and consequently it can be resistively heated to bring the catalyst up to the required light-off temperature. In addition, platinum has been incorporated into the crystal structure to give improved low temperature light-off while having a low platinum vapor pressure at high operating temperatures. This catalyst can be used in powdered form, by washcoating it onto a high temperature ceramic substrate, or as sintered monolythic structures, e.g. plates. The advantage of using the catalyst in the form of plates, for example, is that they can be resistively heated to assist light-off. However, the catalyst is more readily available in powdered form and therefore the first tests with the new catalyst have been made with it washcoated on a honeycomb substrate. The substrate used was mullite, three inches long with 1/16 inch square cells. Experiments using perovskite powders with both 0.1% (by weight) and 1.0% (by weight) platinum content and pure platinum have been conducted. The tests consist of establishing the light-off temperature for several equivalence ratios and inlet velocities, after which the catalyst is "aged" at 1300 °K and then the light-off experiments repeated. Results from these tests can be used as a guide in the selection of the optimum platinum content, in terms of both adequate low temperature light-off and minimal high temperature aging.

CATALYTIC COMBUSTION PROGRAM (AFOSR-81-0248)

EXPERIMENTAL SCHEMATIC



TEST SECTION DETAIL

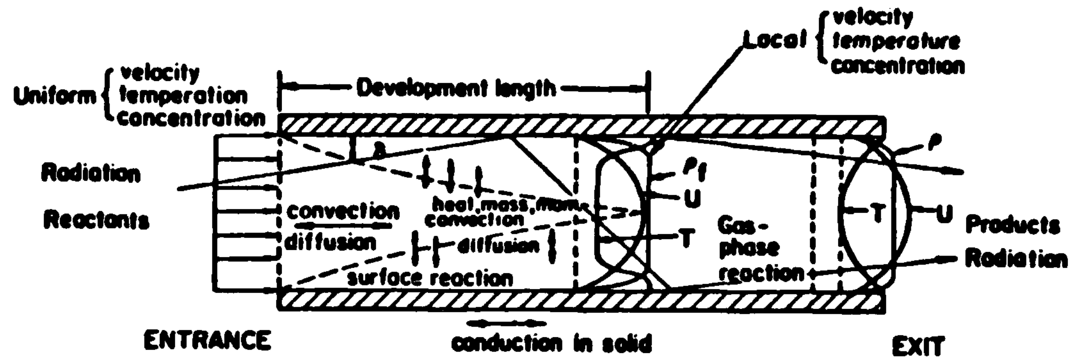


MEASUREMENTS MADE OVER RANGE OF TYPICAL AFTERBURNER CONDITIONS

* SUBSTRATE TEMPERATURE PROFILES
* EXHAUST GAS TEMPERATURE AND COMPOSITION PROFILES

DEVELOPMENT OF NEW CATALYST

* PEROVSKITE CATALYST FOR HIGH TEMPERATURE ENDURANCE AND CATALYTIC ACTIVITY
* PLATINUM ADDED TO CRYSTAL STRUCTURE FOR LOW TEMPERATURE LIGHT OFF AND HIGH TEMPERATURE STABILITY
* ELECTRICALLY CONDUCTIVE FOR INDEPENDENT IGNITION CONTROL BY RESISTIVE HEATING
* LOW TEMPERATURE PERFORMANCE TESTS BEFORE AND AFTER HIGH TEMPERATURE AGING



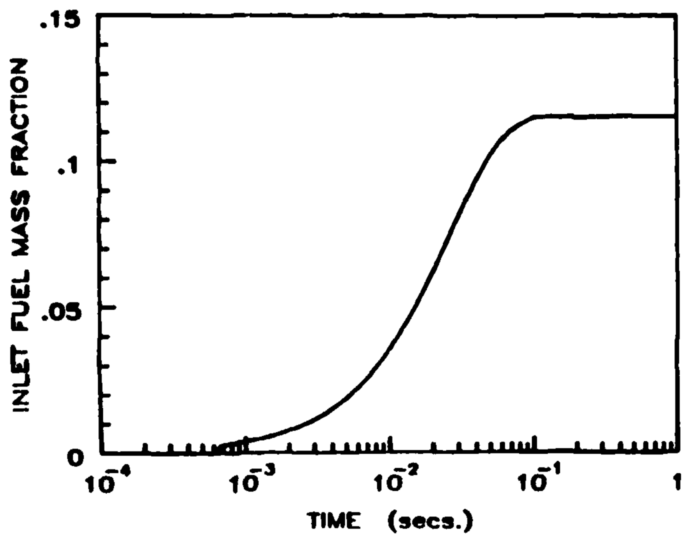
TWO DIMENSIONAL, TRANSIENT MODEL

* INCLUDES - COUPLING BETWEEN GAS AND SUBSTRATE
  - RADIATIVE HEAT LOSS
  - GAS AND SURFACE REACTIONS
* PREDICTS TRANSIENT AND STEADY STATE
  - TWO DIMENSIONAL SUBSTRATE TEMPERATURE
  - TWO DIMENSIONAL GAS TEMPERATURE AND COMPOSITION INSIDE CATALYST
  - EXHAUST TEMPERATURE AND COMPOSITION PROFILES
* COMPARISON WITH STEADY STATE CO/AIR EXPERIMENTS

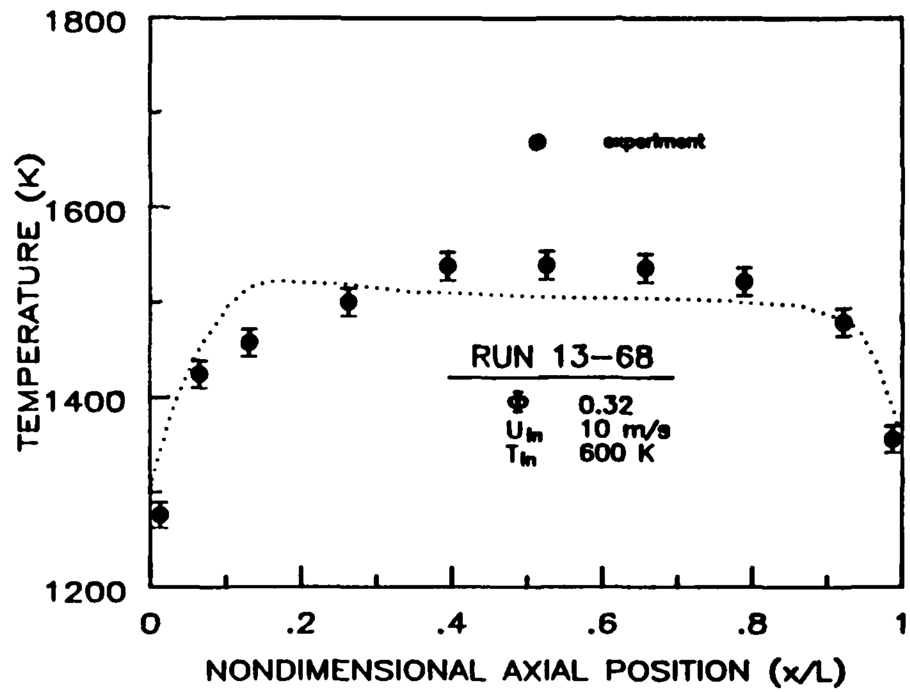
INLET CONDITIONS FOR TRANSIENT CALCULATION

Velocity	10 m/sec
Temperature	600° K
Pressure	110 KPa
Fuel	Carbon Monoxide
Equivalence Ratio	0.32
Adiabatic Flame Temperature	1580° K
Water Mole Fraction	5.4×10^{-3}
Mach Number	0.02
Reynold's Number	290

FUEL TRANSIENT



COMPARISON OF PREDICTED AND MEASURED SUBSTRATE TEMPERATURE PROFILES



RADIATION ENHANCED IGNITION, COMBUSTION AND FLAME STABILIZATION

I. Crane

Exxon Research and Engineering Company

<u>ABSTRACT NOT AVAILABLE</u>

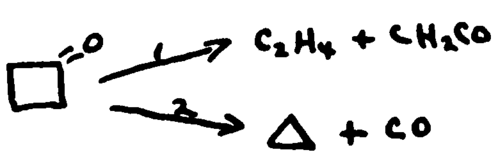
THE INFLUENCE OF I.R. LASER RADIATION ON THE IGNITION AND COMBUSTION OF FUELS

Walter Braun and Milton D. Scheer

Chemical Kinetics Division
National Bureau of Standards
Washington, D. C. 20234

The intent of this research is to investigate the effects of intense I.R. laser radiation on the kinetic behavior of hydrocarbon-like molecules that are heated to temperatures where their unimolecular decomposition rates are fast enough to be in the non-thermal fall-off regime. Under these circumstances the vibrational energy distribution departs from thermal equilibrium in that there is a depletion of the Boltzmann high energy tail in the region of the activation energy and beyond. The absorption of a sufficient number of I.R. photons by the energized molecules of such a reacting system can in principle tend to re-establish the Boltzmann distribution and thereby enhance the decomposition rate.

An experimental methodology has been developed which can readily distinguish between laser heating and the specific laser pumping of those molecules with vibrational energies near the activation energy. A schematic diagram of the apparatus is shown in Figure 1. The method involves the simultaneous measurement of the rates of decomposition of a single molecule into two separate reaction channels. A convenient example of such a system is the decomposition of cyclobutanone whose two reaction channels and Arrhenius parameters are as follows:



$$3.63 \times 10^{14} \exp\left(-\frac{52{,}000}{RT}\right)$$

$$2.34 \times 10^{14} \exp\left(-\frac{58{,}000}{RT}\right)$$

Figure 2 gives the detailed kinetic equations for a thermalized system at the high pressure limit. Figure 3 shows linear plots of $\ln\left(\frac{1+P_1/P_2}{Z}\right)$ vs. $\ln\left(\frac{1+P_2/P_1}{Z}\right)$. The quantities P_1 and P_2 are the product yields in channels 1 and 2 and Z is $\ln\left(\frac{1}{1-f_1-f_2}\right)$ where the f's are the fractional yields for each of the two channels. When SF_6 is the heat bath gas, a lowering of the pressure reduces the rates of both pathways. Departures from the high pressure limit are observed as different reaction temperatures generate the data for the least square lines in Figure 3. A decrease in the collision efficiency for the transfer of vibrational energy by the heat bath gas (i.e. changing from SF_6 to He and Ar) displaces the experimental lines further into the fall-off regime.

The absorption of I.R. photons by the reacting molecules is analagous to the collisional transfer of vibrational energy from the heat bath. One can therefore expect a displacement of the data towards the high pressure limit when such a reacting system is laser irradiated at suitable wavelengths and at high enough power levels. The dotted line in Figure 3 shows the expected result when a mixture of 60 μtorr of cyclobutanone in 2 torr of Ar is so irradiated and heated to temperatures in the neighborhood of 1100K.

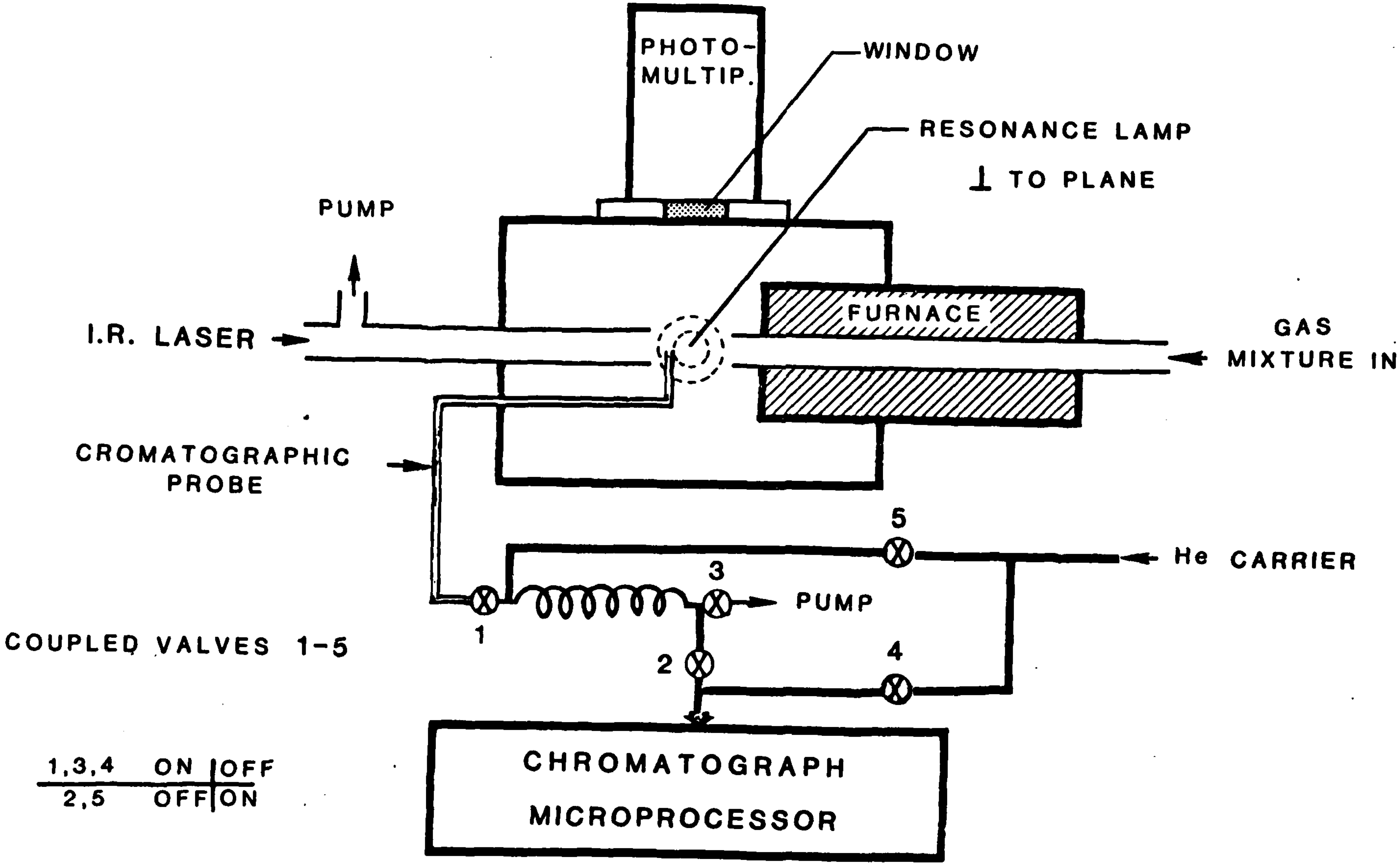


PHOTO-
MULTIP.
WINDOW
RESONANCE LAMP
⊥ TO PLANE
PUMP
I.R. LASER
FURNACE
GAS
MIXTURE IN
CROMATOGRAPHIC
PROBE
5
He CARRIER
3
PUMP
1
COUPLED VALVES 1–5
2
4
1,3,4 ON | OFF
2,5 OFF | ON
CHROMATOGRAPH
MICROPROCESSOR

$$R \begin{array}{l} \xrightarrow{K_1} P_1 \qquad K_1 = A_1 e^{(-E_1/RT)} \\ \xrightarrow{K_1} P_2 \qquad K_2 = A_2 e^{(-E_1/RT)} \end{array}$$

$$f_1 = P_1/R_0;\ f_2 = P_2/R_0;\ 1 - f_1 - f_2 = e^{-(K_1 + K_2)t}$$

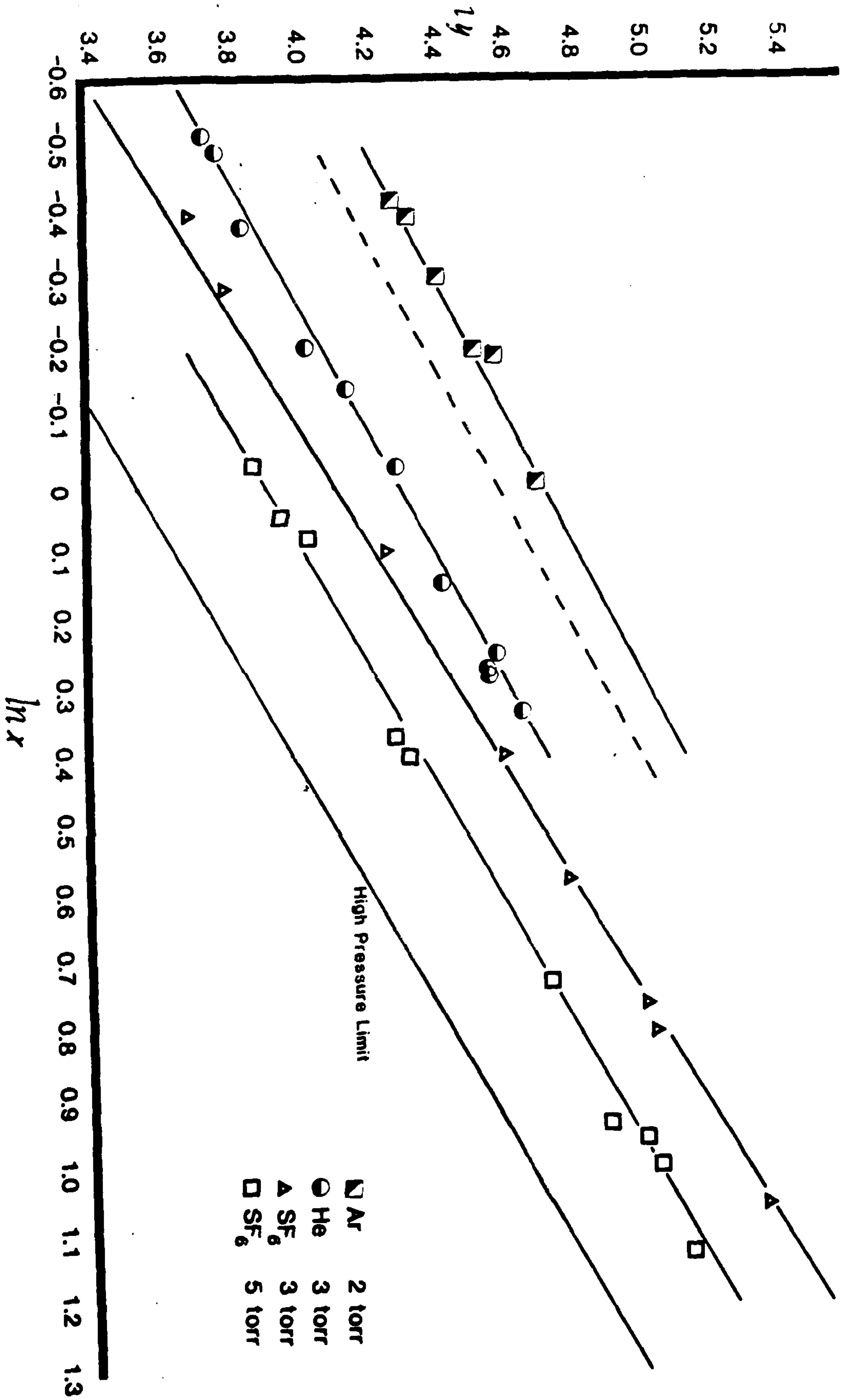
$$Z = \mathrm{LN}\left(\frac{1}{1 - f_1 - f_2}\right)$$

$$Y = \left(1 + \frac{P_1}{P_2}\right)/Z$$

$$X = \left(1 + \frac{P_2}{P_1}\right)/Z$$

$$\mathrm{LN}(Y) = \frac{E_2}{E_1}\,\mathrm{LN}(X) + \mathrm{LN}\left(\frac{A_1}{A_2}\right)^{E_2/E_1} + \mathrm{LN}\left(t^{\left(\frac{E_2}{E_1} - 1\right)}\right)$$

FIGURE 2


ly
3.4
3.6
3.8
4.0
4.2
4.4
4.6
4.8
5.0
5.2
5.4
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
lnx
High Pressure Limit
Ar 2 torr
He 3 torr
SF6 3 torr
SF6 5 torr

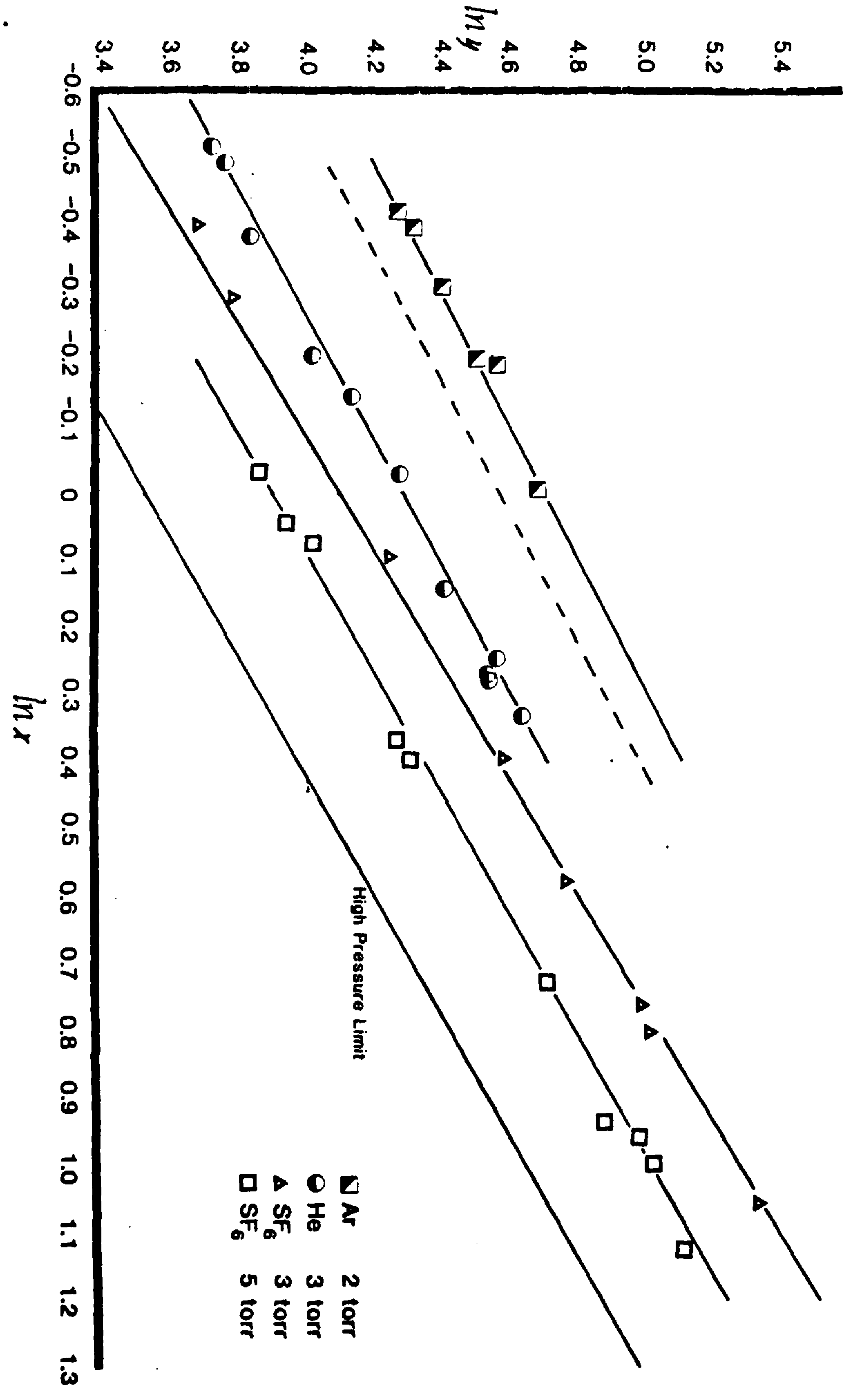

ln y
ln x
5.4
5.2
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
High Pressure Limit
Ar 2 torr
He 3 torr
SF_6 3 torr
SF_6 5 torr

FIGURE 3

STABILIZATION OF FIRES BY LARGE-SCALE FLAMEHOLDERS (AF 820107)

Arthur H. Lefebvre

School of Mechanical Engineering

Purdue University, West Lafayette, IN 47907

Stabilization of fires on aircraft can arise due to external fuel leakage caused by combat damage to fuel tanks. If leaking fuel is entrained into the air recirculation zones that always exist near the tail section of an aircraft, or into wake regions created by structural damage to the fuselage, then any source of ignition, such as a hot surface, hot gas or frictional spark would produce a stabilized flame that could lead to loss of the aircraft. It would clearly be advantageous to be able to predict the conditions needed to sustain (and extinguish) such external fires. However, although a considerable body of information exists in the literature on flame stabilization by bluff bodies, it makes little or no contribution to the solution of the aircraft fire problem because it was all obtained on small flameholders having characteristic dimensions of usually less than 2 cm.

A main objective of the present research is to extend the range of experimental data on the stabilization properties of bluff-body flameholders to include flameholders of large size (characteristic dimension up to 10 cm) and irregular shape. Another goal is to derive suitable theoretical relationships to describe stabilization performance for the extended range of flameholder sizes and shapes.

Stability loops are obtained by the water injection technique, as shown schematically in Figure 1. The flameholder under test is placed near the exit of a duct supplied with an airflow containing a water/fuel mixture. Both the water and fuel are fully vaporized by the time they reach the flameholder. At the start of a run the fuel/air ratio is set and the flame is established with no water injection. The water flow is then initiated and increased until flame extinction occurs. A plot of the stability loop so obtained (equivalence ratio versus water/fuel ratio) is equivalent to a plot of equivalence ratio versus the reciprocal of pressure. The calculated relationship between water/fuel ratio and the equivalent reduction in gas pressure is shown in Figure 2 from reference 1. It illustrates, for example, that the injection of equal weights of water and fuel is equivalent to halving the pressure. The method has two advantages: it is the only technique that allows the entire stability loop to be obtained for large flameholders, and any subatmospheric pressure can be simulated while using fan air at atmospheric pressure.

The test facility is now in full operational use and stability loops for flameholders of different sizes and shapes are being obtained as a routine procedure. Some recent results are shown in Figures 3 to 5. Figure 3 shows the stability loops obtained by locating a metal plate at an angle θ to the duct wall. This produces a single-sided flow recirculation in its wake, and simulates closely the type of flameholder that would be produced by damage to an aircraft structure which caused a portion of the aircraft skin to project outwards into the air stream. The results indicate that flame stability is improved by an increase in θ. Figures 4 and 5 show the influence of fuel type on stability for single-sided and double-sided flow recirculations respectively. The effect of fuel type on stability is manifested through its influence on laminar flame speed, as indicated in the following equations from reference 3.

$$U_{BO} = C_s \ (1 - B_a)(D_c \ S_L^{2}/\alpha)$$

$$U_{BO} = C_s \ (1 - B_a) \ Re \ Pr$$

Thus blowoff velocity is governed mainly by the flame speed of the fuel and the size of the flameholder. Predictions of blowoff velocity based on the above equations agree closely with corresponding experimental values obtained for several fuels over wide range of air temperature, air velocity, flameholder size and flameholder blockage.

References

1. Greenhough, W. V. and Lefebvre, A. H., "Some Applications of Combustion Theory to Gas Turbine Development, Sixth Symposium (International) on Combustion, pp. 858-869, 1957.

2. Ballal, D. R. and Lefebvre, A. H., "Some Fundamental Aspects of Flame Stabilization", Fifth International Symposium on Airbreathing Engines, Bangalore, India, February 1981.

3. Rao, K. V. L. and Lefebvre, A. H., "Flame Blowoff Studies Using Large-Scale Flameholders", ASME Paper 82-GT-36, 27th Gas Turbine Conference, London, 1982.

FLAME STABILIZATION

PROBLEM

- VERY LITTLE IS KNOWN ABOUT THE STABILIZATION PROPERTIES OF LARGE FLAMEHOLDERS AND FLAMEHOLDERS OF IRREGULAR SHAPE, SUCH AS MIGHT BE CREATED ON THE EXTERNAL SURFACE OF AN AIRCRAFT DUE TO STRUCTURAL DAMAGE.

NEEDS

- EXPERIMENTAL DATA ON LARGE-SCALE FLAMEHOLDERS
- THEORETICAL RELATIONSHIPS TO DESCRIBE STABILIZATION PERFORMANCE FOR WIDE RANGES OF FLAMEHOLDER SIZE AND SHAPE, AND FOR VARIOUS FUELS

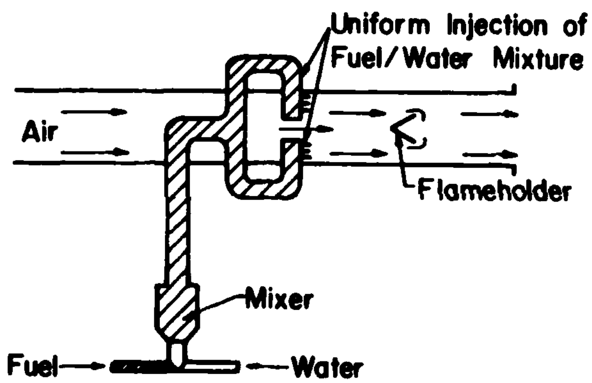


Figure I Schematic Diagram of Test Rig

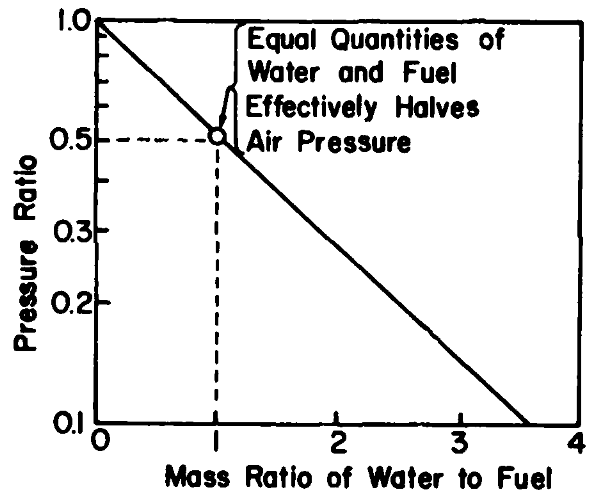


Figure 2 Relationship Between Water/Fuel Ratio and Effective Pressure Ratio

APPROACH

- WATER INJECTION TECHNIQUE WHICH ALLOWS A COMPLETE STABILITY LOOP TO BE OBTAINED FOR LARGE FLAMEHOLDERS, USING AN AIR SUPPLY AT ATMOSPHERIC PRESSURE

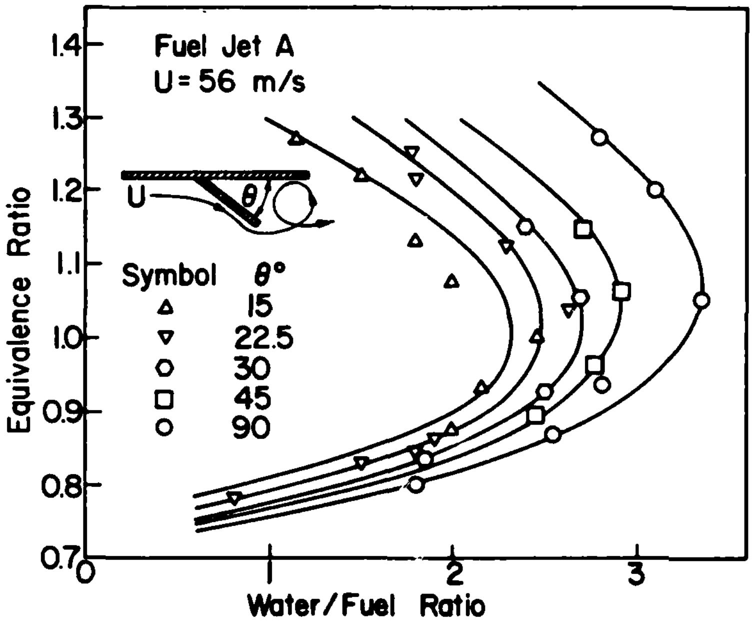


Figure 3

Experimental Data Show That

$$U_{BO}/S_L = C_s\,(1-B_a)\,Re\,Pr$$

where U_{BO} = Blowoff Velocity

S_L = Laminar Flame Speed

C_s = Flameholder Shape Factor

B_a = Aerodynamic Blockage of Flameholder

Re = Reynolds Number Based on Flame Speed

Pr = Prandtl Number

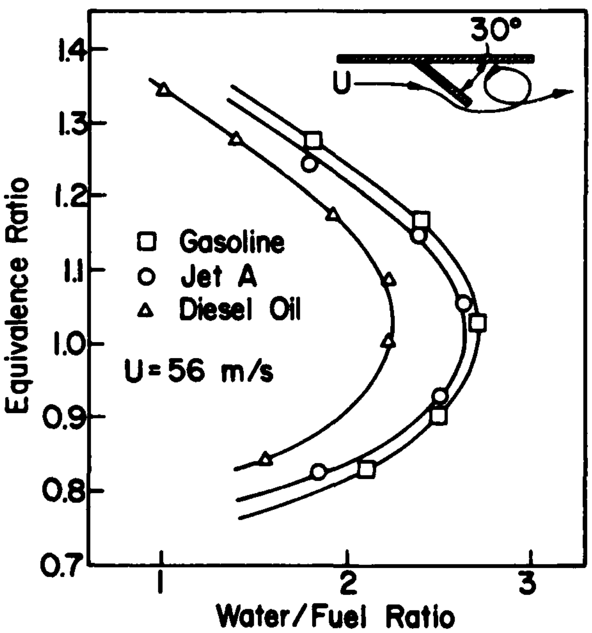


Figure 4

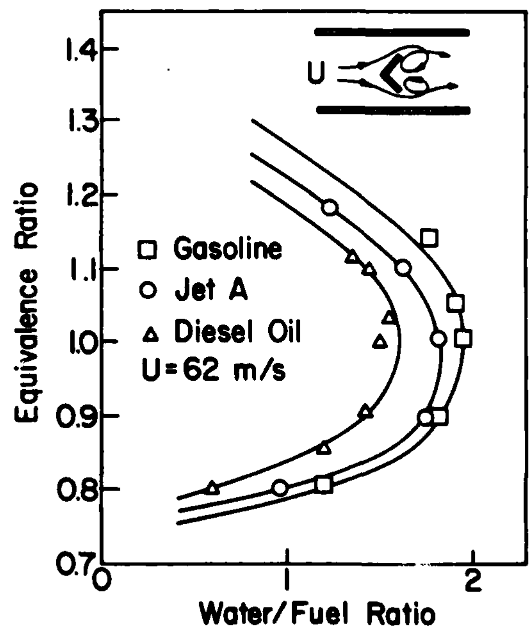


Figure 5

STABILIZATION OF VOID SPACE FIRES

(AFOSR 82-0107)

S.N.B. Murthy
School of Mechanical Engineering
Purdue University
West Lafayette, Indiana 47907

The void spaces under consideration are relatively small volume, but length-to-cross section dimension larger than unity, spaces adjacent to a fuel tank. Gun fire puncturing the outer skin and then the fuel tank material is one of the principal causes of fires in those spaces and it is of interest to establish the propagation and stability characteristics of such fires. A void space may be considered for purposes of analysis as a small cavity with negligibly small primary ventilation into which a low velocity jet of fuel enters from one wall and an induced air flow arises from a small opening in the opposite wall. Ignition is expected to arise during the terminal phase of an incendiary projectile and the flame may become stabilized at the protrusions generated at the point of impact of the projectile on the fuel tank. In view of the complex flow pattern arising in a cavity with arbitrary geometry, ignition may also occur at various locations in the cavity. The flame propagation and stabilization within a cavity and in different cavities when a series of cavities are interconnected, as is often the case in practice, are the central considerations in the evolution of design of void spaces and the control of fire therein.

Several parameters that play an interactive role in the problem are as follows: (a) material and construction of outer skin, fuel tank and void space contents, (b) fuel characteristics, (c) projectile calibre and incendiary characteristics and (d) the nature of impact of the projectile. These parameters affect (a) fuel admission, (b) ignition, (c) flame-holding, (d) air induction and (e) flame propagation and stability. Of these, air flow induction presents the greatest uncertainty both as a cause and as an effect; it may also be pointed out that the air flow vent could act simultaneously as an opening for gases from within the cavity to escape to the outside. Past researches have demonstrated the influence of chemical time and residence time, which in turn are related to certain velocity, length and chemical action scales, but air flow induction and its consequences have not been included in such studies.

Current Status and Plans

Since the inception of the research project on November 15, 1981, based on a survey of research and testing activity in the subject, analytical and experimental studies have been undertaken.

Analytical studies have consisted in examining the applicability of the following individually and in combination.

(i) One-dimensional or control volume analysis of cavity flow with a heat source generating high temperature gases and under the influence of pressure differentials and buoyancy.

(ii) UNDSAFE-II Code developed for two-dimensional flow analysis in cavities with fire.

(iii) Los Alamos and Imperial College Codes for three-dimensional flow analysis with added chemistry and buoyancy effects.

(iv) Segreated stirred reactors with stochastic mixing filling the cavity in a given configuration initially.

(v) Instability analysis incorporated into (iii) or (iv).

In each case (i) to (iv), a method of including induced air flow is being examined. The central difficulty is in establishing the local pressure differential driving the air flow under steady and nonsteady conditions.

The experimental part of the program has evolved as follows:

A basic cavity configuration with external air flow and with fuel feed when necessary has been developed. The external air flow could be up to 300 feet per second and the pressure differential between the external conditions and the cavity could be up to 2.0 psig.

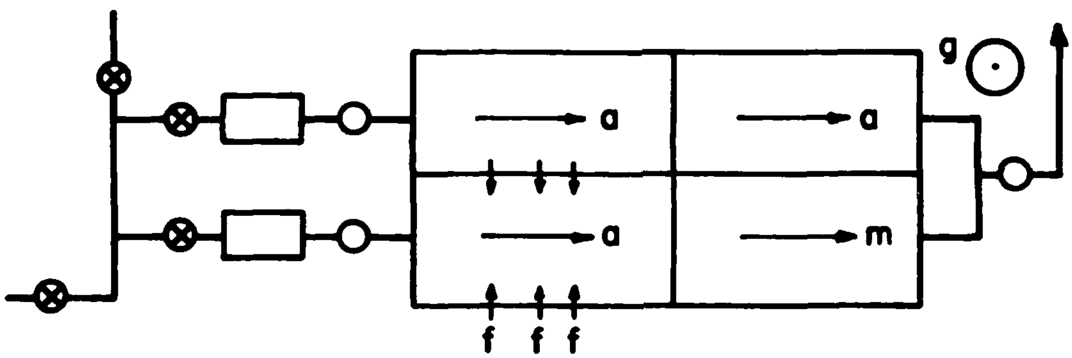
The first cavity tests will be conducted with a cavity incorporating transparent walls. The air flow will be visualized and also measured to obtain a flow field map by using the following as parameters: the location of the air flow vent holes and the pressure differential between the cavity and the external flow. While the measurements will be confined to steady state values, flow visualization will reveal instabilities, if any, in various parts of the cavity.

The next level of experiments will introduce a marker-gas in place of the fuel jet. Once again, steady state measurements of concentration distribution and flow visualization to reveal the nature of instabilities will be undertaken. It will be of special interest to examine (a) the formation of pockets of injected gas and (b) the instabilities in the vicinity of the air and fuel vents.

The next and final stage of experiments will involve combustion of fuel. In this case both single and multiple cavities will be employed. In order to establish and to quantify the instabilities, a laser interferometer is expected to be developed.

ACCOMPLISHMENTS

- Period: 11-15-81 through 10-1-82
- Survey of Status
  - Direct: WPAFB; ADL; FRAJ
  - Basic
    - Fluid Mechanics with Buoyancy
    - Two and Four Layer Models
    - Dimensional Analysis of Interactions
- Experimental Studies



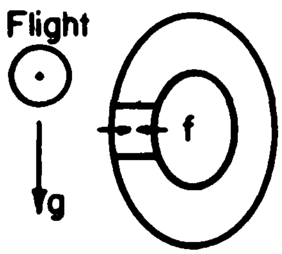
- Test Section: 15×10×60 cms.
- Free Air Flow Velocity: 20–100 m/s.

<u>Basic Experimental Set Up</u>

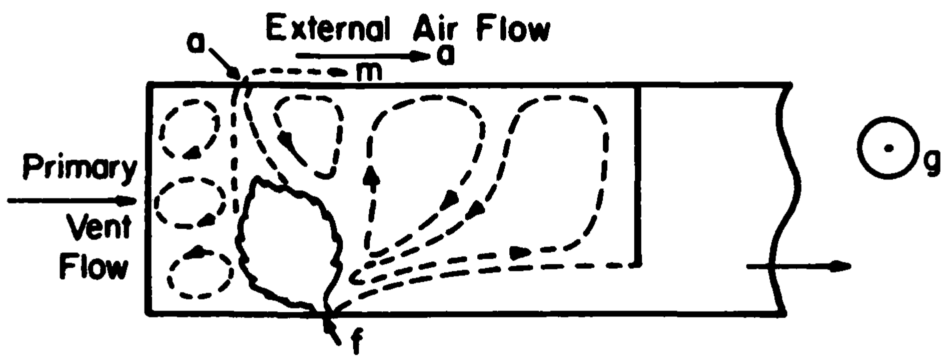
- Inert Flows
  - Flow Visualization
  - Basic Measurements
- Combustion Experiments
- Analytical Studies
  - Predictions
    - UNDSAFE-II
    - Los Alamos / Imperial College Codes
      - Buoyancy
      - Chemistry
  - Instability Model
    - Segregated Stirred Reactors with Stochastic Mixing

STABILITY OF VOID SPACE FIRES
AFOSR–82–0107 Part III

- Internal Fires Adjacent to Fuel Tank
    - Complex Geometry
    - Small Primary Ventilation
    - Fire Generated by Incendiary Gun Fire
    - Fire Stability and Propagation
- Design of Void Space Configurations and Control of Fire Propagation
    - Projectile Impact • Fuel Spill
    - Ignition • Multiple Flames
    - Induced Air Flow • Induced Fuel Flow
- Effect of Buoyancy
    - Roof and Side Vented Cases



Fuel Tank in Fuselage



An Example of Flow Pattern

- Approach
    - Experimental Studies
        - Diagnostic
        - Mean Flow Field and Concentration Measurements
        - Detailed Nonsteady Patterns Using Laser
        - Interferometry
    - Numerical–computational Flow Visualization
        - Two-dimensional • Three-dimensional
    - Determination of Principal Transient Regimes in Fluid Mechanical–Chemistry Interactions
        - Oscillatory Conditions
            - Flame Propagation
        - Quenching and Reignition

STABILIZATION OF VOID SPACE FIRES

(AFOSR 82-0107)

S.N.B. Murthy
School of Mechanical Engineering
Purdue University
West Lafayette, Indiana 47907

The void spaces under consideration are relatively small volume, but length-to-cross section dimension larger than unity, spaces adjacent to a fuel tank. Gun fire puncturing the outer skin and then the fuel tank material is one of the principal causes of fires in those spaces and it is of interest to establish the propagation and stability characteristics of such fires. A void space may be considered for purposes of analysis as a small cavity with negligibly small primary ventilation into which a low velocity jet of fuel enters from one wall and an induced air flow arises from a small opening in the opposite wall. Ignition is expected to arise during the terminal phase of an incendiary projectile and the flame may become stabilized at the protrusions generated at the point of impact of the projectile on the fuel tank. In view of the complex flow pattern arising in a cavity with arbitrary geometry, ignition may also occur at various locations in the cavity. The flame propagation and stabilization within a cavity and in different cavities when a series of cavities are interconnected, as is often the case in practice, are the central considerations in the evolution of design of void spaces and the control of fire therein.

Several parameters that play an interactive role in the problem are as follows: (a) material and construction of outer skin, fuel tank and void space contents, (b) fuel characteristics, (c) projectile calibre and incendiary characteristics and (d) the nature of impact of the projectile. These parameters affect (a) fuel admission, (b) ignition, (c) flame-holding, (d) air induction and (e) flame propagation and stability. Of these, air flow induction presents the greatest uncertainty both as a cause and as an effect; it may also be pointed out that the air flow vent could act simultaneously as an opening for gases from within the cavity to escape to the outside. Past researches have demonstrated the influence of chemical time and residence time, which in turn are related to certain velocity, length and chemical action scales, but air flow induction and its consequences have not been included in such studies.

Current Status and Plans

Since the inception of the research project on November 15, 1981, based on a survey of research and testing activity in the subject, analytical and experimental studies have been undertaken.

Analytical studies have consisted in examining the applicability of the following individually and in combination.

(i) One-dimensional or control volume analysis of cavity flow with a heat source generating high temperature gases and under the influence of pressure differentials and buoyancy.

(ii) UNDSAFE-II Code developed for two-dimensional flow analysis in cavities with fire.

(iii) Los Alamos and Imperial College Codes for three-dimensional flow analysis with added chemistry and buoyancy effects.

(iv) Segreated stirred reactors with stochastic mixing filling the cavity in a given configuration initially.

(v) Instability analysis incorporated into (iii) or (iv).

In each case (i) to (iv), a method of including induced air flow is being examined. The central difficulty is in establishing the local pressure differential driving the air flow under steady and nonsteady conditions.

The experimental part of the program has evolved as follows:

A basic cavity configuration with external air flow and with fuel feed when necessary has been developed. The external air flow could be up to 300 feet per second and the pressure differential between the external conditions and the cavity could be up to 2.0 psig.

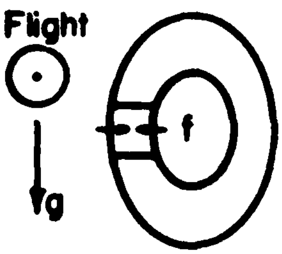
The first cavity tests will be conducted with a cavity incorporating transparent walls. The air flow will be visualized and also measured to obtain a flow field map by using the following as parameters: the location of the air flow vent holes and the pressure differential between the cavity and the external flow. While the measurements will be confined to steady state values, flow visualization will reveal instabilities, if any, in various parts of the cavity.

The next level of experiments will introduce a marker-gas in place of the fuel jet. Once again, steady state measurements of concentration distribution and flow visualization to reveal the nature of instabilities will be undertaken. It will be of special interest to examine (a) the formation of pockets of injected gas and (b) the instabilities in the vicinity of the air and fuel vents.

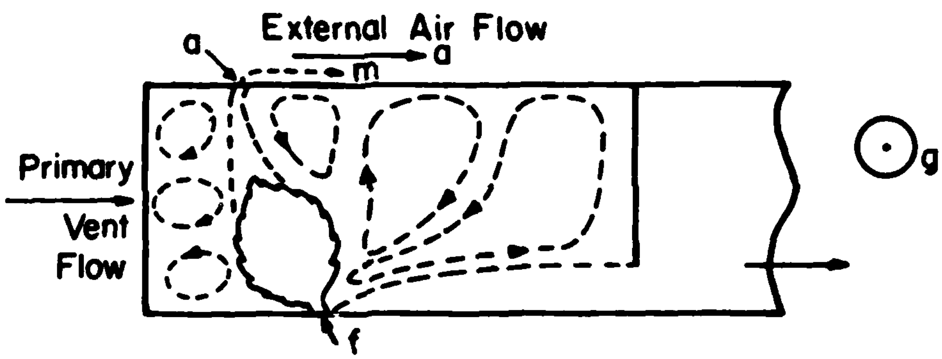
The next and final stage of experiments will involve combustion of fuel. In this case both single and multiple cavities will be employed. In order to establish and to quantify the instabilities, a laser interferometer is expected to be developed.

STABILITY OF VOID SPACE FIRES
AFOSR-82-0107 Part III

- Internal Fires Adjacent to Fuel Tank
  - Complex Geometry
  - Small Primary Ventilation
  - Fire Generated by Incendiary Gun Fire
  - Fire Stability and Propagation
- Design of Void Space Configurations and Control of Fire Propagation
  - Projectile Impact • Fuel Spill
  - Ignition • Multiple Flames
  - Induced Air Flow • Induced Fuel Flow
- Effect of Buoyancy
  - Roof and Side Vented Cases



<u>Fuel Tank in Fuselage</u>

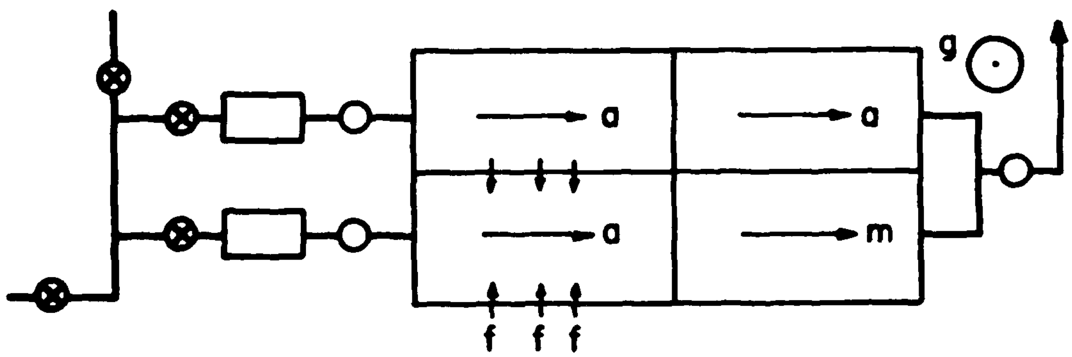


<u>An Example of Flow Pattern</u>

- Approach
  - Experimental Studies
    - Diagnostic
    - Mean Flow Field and Concentration Measurements
    - Detailed Nonsteady Patterns Using Laser
    - Interferometry
  - Numerical-computational Flow Visualization
    - Two-dimensional • Three-dimensional
  - Determination of Principal Transient Regimes in Fluid Mechanical-Chemistry Interactions
    - Oscillatory Conditions
      - Flame Propagation
    - Quenching and Reignition

ACCOMPLISHMENTS

- Period: 11-15-81 through 10-1-82
- Survey of Status
  - Direct: WPAFB; ADL; FRAD
  - Basic
    - Fluid Mechanics with Buoyancy
    - Two and Four Layer Models
    - Dimensional Analysis of Interactions
- Experimental Studies



- Test Section: 15×10×60 cms.
- Free Air Flow Velocity: 20–100 m/s.

<u>Basic Experimental Set Up</u>

- Inert Flows
  - Flow Visualization
  - Basic Measurements
- Combustion Experiments
- Analytical Studies
  - Predictions
    - UNDSAFE-II
    - Los Alamos / Imperial College Codes
      - Buoyancy
      - Chemistry
  - Instability Model
    - Segregated Stirred Reactors with Stochastic Mixing

IGNITION OF FUELS BY INCENDIARY PARTICLES AND HOT BODIES

W. A. Sirignano and H. T. Sommer

Department of Mechanical Engineering
Carnegie-Mellon University
Pittsburgh, PA 15213

The purpose of the latest phase of this experimental and theoretical program is to study the ignition of fuel/air sprays by hot surfaces. The reporting from previous years' efforts has emphasized gas-phase ignition by hot bodies. Both "stagnant" and flowing sprays are considered now. The study is motivated by safety factors whereby ignition is undesirable and propulsion and energy considerations whereby rapid ignition is very desirable.

A common approach in the theoretical study of spray combustion involves the treatment of the two-phase problem by a two-continua approach whereby point-wise values of gas-phase and liquid phase properties represent averages in the neighborhood of the point. This method is currently being employed to study ignition of fuel/air sprays by hot plates and spheres. Preliminary numerical results show the time-dependent behavior of the gas and liquid droplets during the ignition and flame establishment periods. Plate temperature, fuel volatiltiy, mixture ratio, droplet size, and droplet number density are some of the interesting parameters observed to affect ignition delays.

This continuum approach becomes inconsistent and subject to large errors when ignition delay is sufficiently short or droplet number density is not so large that the thermal wave thickness by the plate is not at least one or two orders of magnitude greater than the average distance between the droplets. Such a situation is fairly common requiring an examination on the scale of the distance between droplets. At present, a formulation of this problem modelled in terms of an array of droplets in the vicinity of a hot surface has been made. The intention of this formulation is to predict ignition delay for the droplets in the array layer nearest the hot surface and then to predict ignition delays for the next layer of droplets and so forth. Single droplet results will be employed in a modified form to obtain these results. The results of both theoretical approaches will be placed in a form whereby they can be compared to experimental results. In the experimental program, the ignition characteristics of fuel droplets in a co-flowing saturated fuel/air mixture impinging on hot bodies of several geometries will be examined.

The heating of the body will be resistive (except in the case of the particle which will be heated using a laser). The three basic geometries that are being explored are the cylinder, plate and sphere or particle. For the cylinder, its geometry is such that $d \ll \ell$ so that we can use thin wire. Ignition properties of the wire will be studied at three different diameters for this experiment. They are as follows: 0.05mm, 0.1mm and 0.5mm. Next, a thin hot plate geometry will be examined. For this case, the length parallel to the droplet flow will be of the same order of magnitude as the width of th plate. Keeping width constant, several plate lengths will be examined. For this parallel-to-flow orientation there will be three aspect ratios under study and one thickness. Finally, ignition of the spray mixture by small burning particles (ignited by a Nd/Glass pulse laser) will be observed. The size range of the particles will vary to the upper and lower limits of mixture ignition (i.e., probably 30-100μ).

A technique has been developed whereby the vapor pressure of the co-flowing fuel/air mixture will be varied by the use of a constant temperature water bath; this allows for leaner and richer fuel mixtures. The volume flowrate of air, and, thus, the velocity of the fuel/air mixture, will be adjusted to obtain an understanding of its effect on ignition. The diameter of the hot wire or the length of the plate affects the critical values of the velocity and the mixture ratio. Finally, for each geometry, the mass flow of the spray and the droplet size can be altered. The diameter of the hot wire or the length of the plate affects the critical values of the velocity and the mixture ratio.

Additionally, it would be interesting to study the dynamic situation as seen by the hot body. The equivalence ratio of the fuel/air mixture will be lower than the overall equivalence ratio which includes the fuel in the droplets. Concern centers on whether the hot body will ignite the surrounding fuel/air mixture at the lower equivalence ratio or will it wait until the fuel droplets in the vicinity of the body evaporate, raising the local equivalence ratio to one more suitable to ignition. Also, if droplets impinge on the body and wet it, it is necessary to know whether or not the evaporation of this liquid fuel will consume too much heat to allow for combustion.

Once again, to study the ignition phenomena various diagnostic equipment will be used. This will include: photomultiplier tube and oscilloscope, optical pyrometer and oscilloscope, gas chromatograph and high-speed cinematography equipment which should eventually include high speed schlieren. The system is depicted in Figure 1.

Accomplishments to date are summarized in Table 1.

TABLE I

ACCOMPLISHMENTS

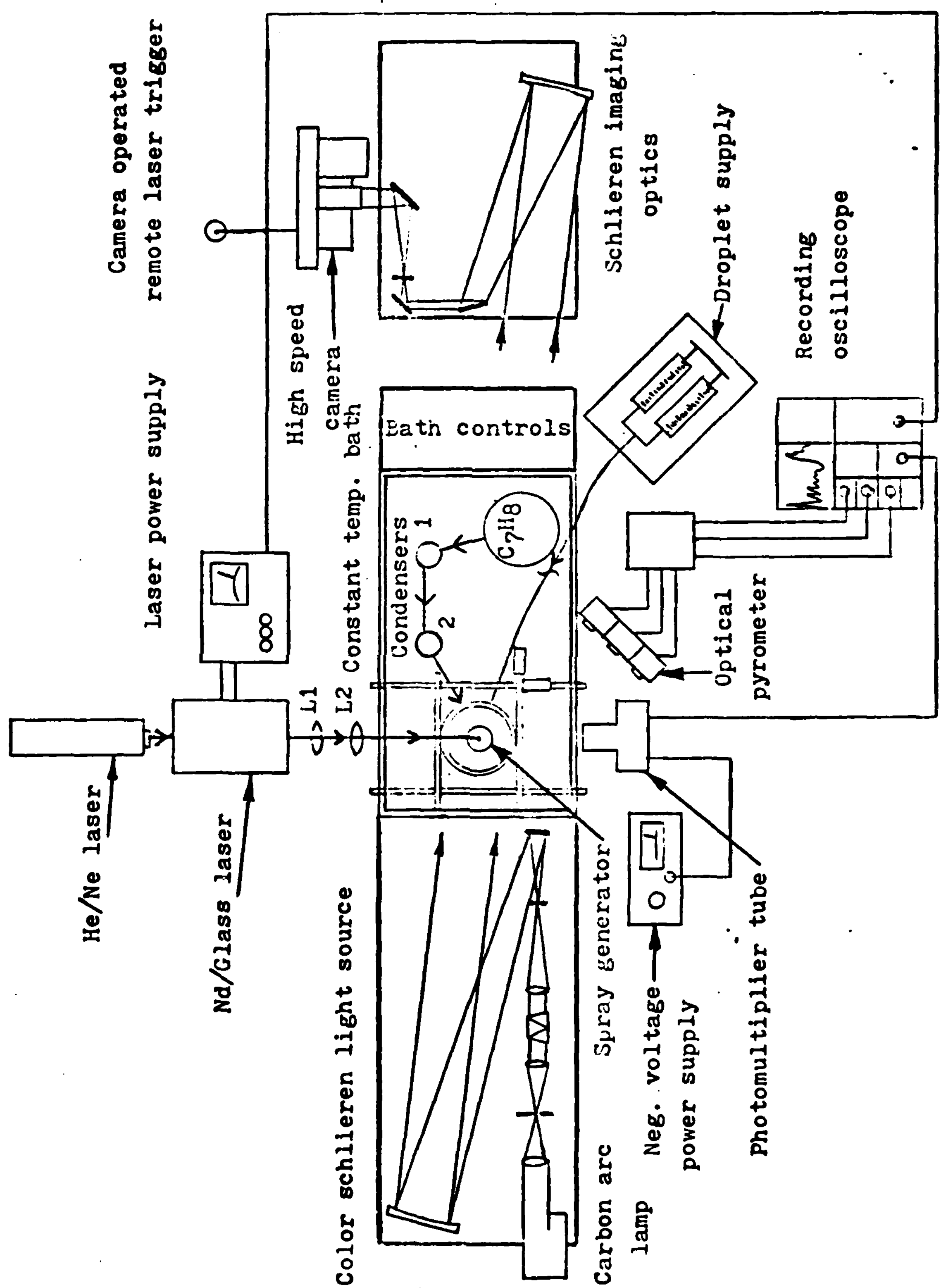
1. Completion of Experiments and Theory on Ignition of Gaseous Mixtures by Hot Particles: Determination of Effects of Mixture Ratio, Particle Size and Particle Temperature on Ignition Delays

2. One-dimensional, Unsteady Solution of Ignition and Flame Establishment in a Fuel/Air Spray by a Hot Plate: Numerical analysis with a Continuum Approach

3. Spherically-symmetric Calculation (in progress) of Ignition and Flame Establishment via a Hot Sphere: Numerical Analysis with a Continuum Approach

4. Formulation of Microscale Approach for Situations where Thermal Wave Thickness is Comparable to Droplet Spacing

5. Design and Development of Experimental Apparatus and Technique for Spray Ignition Studies



Camera operated
remote laser trigger
Laser power supply
High speed
camera
Schlieren imaging
optics
Droplet supply
Recording
oscilloscope
Bath controls
Constant temp. bath
Condensers
1
2
C_7H_8
L1
L2
Optical
pyrometer
He/Ne laser
Nd/Glass laser
Color schlieren light source
Spray generator
Carbon arc
lamp
Neg. voltage
power supply
Photomultiplier tube

FIGURE 1.

Thermal Radiative Ignition of a Liquid Fuel

T. Kashiwagi, T.J. Ohlemiller and W. Jones

National Bureau of Standards

Washington, D.C. 20234

High power lasers are now being developed as tactical weapons. Such lasers pose a threat to aircraft integrity by ignition of jet fuel and subsequent fire or explosion. The objective of this work is to obtain a fundamental understanding of the mechanism of the radiative ignition process and to help provide design guidelines for the improvement of aircraft survivability.

In our previous study, it was found that one of the key mechanisms for ignition of liquid fuels by a CO_2 laser is absorption of the incident CO_2 laser beam by evolved fuel vapor in the gas phase above the irradiated surface, as shown in Fig. 1. Since boiling temperatures (150 ~ 200°C) of liquid fuels are much lower than decomposition temperatures of solid fuels (300 ~ 500°C), the supplemental gas phase temperature increase caused by direct absorption of the incident laser energy for ignition of liquid fuels is critical in raising the gas phase temperature enough to initiate gas phase oxidation reactions and to reach a run-away condition. The amount of the absorption is determined by the absorption coefficient of the fuel vapor at the laser wavelength. However, data on absorption spectra of very large hydrocarbon molecules, which are liquids at room temperature, are extremely limited at elevated temperatures. Therefore, one of the aims of this program in FY82 has been to develop a technique for the measurement of the infrared absorption spectra of liquid fuel vapors at elevated temperatures.

In FY81, we developed a high-speed two-wavelength holographic interferometric technique for simultaneous measurement of temperature and fuel vapor concentration distributions in the gas phase during the pre-ignition period. However, the fringe shift recorded in the movie films was analyzed manually. This fringe shift analysis was somewhat inaccurate and extremely tedious. Therefore, the other aim of this program in FY82 has been to develop automatic measurement of interferometric fringe shifts using a computer and also to determine the accuracy of the data reduction technique.

A single beam infrared absorption measurement system has been constructed; it is described in Fig. 2. The system consists of a well regulated black body (~ 1070°C) as a radiant source, a heated cell with a water jacket (cell length is 15 cm) and a monochromator with a pyroelectric detector. Using three different snap-in type gratings, absorption spectra can be measured from 2 to 11 μm. The cell can be heated up to 600°C. Since ambient water vapor and carbon dioxide are good absorbers in the wavelength range of interest, the system is enclosed in an air tight, water-cooled box and water-pumped, dry nitrogen is purged through the box and the monochromator during the measurement. At first, the reference signal is measured by scanning the monochromator with high purity nitrogen in the heated cell at the desired elevated temperature. The signal is stored in a laboratory computer. Then, the sample signal is measured by repeating the same scan with an appropriate concentration of a test gas brought to one atmosphere pressure by nitrogen in the cell still at the same temperature as the first scan. The absorption spectrum can be calculated from the difference in the signal between the two scans. Preliminary experiments with CO_2 at elevated temperatures are in progress as a basis for comparison with previous studies. At present, a vapor generator for liquid fuels is under construction. Absorption spectra of decane and 1-decene at various temperatures and concentrations will be measured in the near future.

In the previous year, a high speed two-wavelength holographic interferometry technique was developed. The change in refractive index in the gas phase above the irradiated liquid is influenced by temperature and concentration changes simultaneously; from a knowledge of these dependencies and the fringe shifts at two different wavelengths, the temperature and concentration fields can be calculated. In the experiment, red light (He/Ne laser) and blue light (Ar-ion laser) interferograms are superimposed at each instant on each frame of a high speed 16 mm color movie (500 frames/sec).

In FY82, a more accurate data analysis procedure is under development. The improved procedure is summarized in Fig. 3. After the blue and red interferograms are separated by filters, a black and white negative film of 10 x 12.5cm is made for each interferogram. The light transmission through the film is measured over the entire frame by an automatic scanning densitometer. The range of the spatial resolution of the densitometer is 25 ~ 200 μm, and the number of digitized transmittance values for each frame is around one million points; these are stored on magnetic tape. In defining the locations of the peaks of the fringes, peaks within one scan are determined by taking the derivative of quadratic profiles fitted to a sequence of data points in an interval which is 40% of the peak transmittance (above the background transmittance value). The search for the next peak in the same scan is initiated beyond the point at which the last sequence terminated. Once we obtain all possible peaks with a scan, their orders are matched with those from the previous scan. Unmatched peaks are eliminated. A typical result of a computer generated contour of peak fringes with 1-decene for blue light is shown in Fig. 4. The amount of fringe shifting is counted by the computer. The effects of errors in the fringe shift measurement on the accuracy of the final temperature and concentration distributions are being investigated by comparing an initially specified temperature and vapor concentration with calculated results using both an Abel inversion and a Fourier transformation superposing random error on the calculated fringe shifts. This examination will determine the required accuracy in the measurement of fringe shifts to obtain reasonable accuracy in final temperature and concentration distributions.

PROBLEM

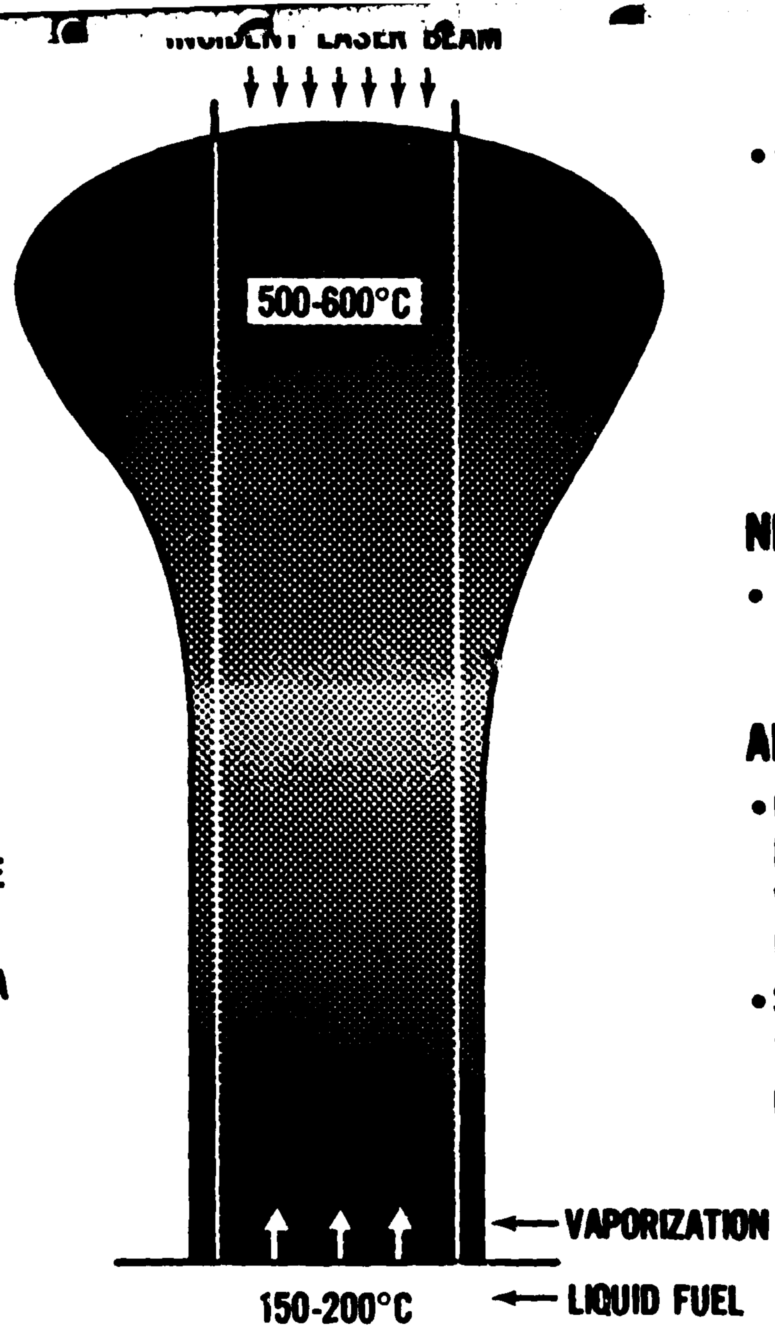
- WHY DO LIQUID FUELS IGNITE BY LASER?
  - KEY PROCESS
    (Gas temperature increase to initiate reactions)
- HOW
  (Absorption of laser energy by vapor)

NEEDS

- ABSORPTION CHARACTERISTICS OF VAPORS AT HIGH T

APPROACH

- CONSTRUCT HIGH TEMPERATURE INFRARED PHOTOMETER
- MEASURE ABSORPTION SPECTRA



- HOW AND WHERE DOES IGNITION OCCUR?
  - KEY PROCESS
    (Time resolved temperature and concentration distribution)

NEEDS

- MEASUREMENTS AT VARIOUS CONDITIONS

APPROACH

- OPTICAL DIAGNOSTICS
  (High speed two-wavelength holographic interferometer)
- SPATIALLY AND TEMPORALLY RESOLVED MEASUREMENTS

ACCOMPLISHMENTS

* COMPLETION OF CONSTRUCTION OF HIGH TEMPERATURE INFRARED ABSORPTION APPARATUS

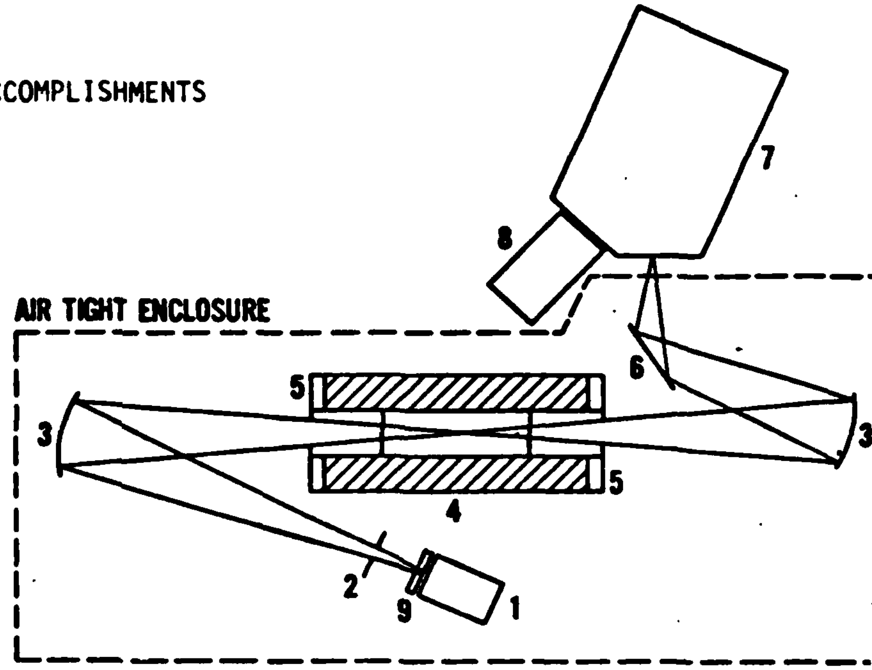


Fig.2 Schematic Illustration of I.R. Absorption Apparatus

1. BLACK BODY
2. CHOPPER
3. CONCAVE MIRRORS
4. HEATED CELL WITH WATER COOLED JACKET
5. WATER COOLED SHIELDS
6. FLAT MIRROR
7. MONOCHROMATOR
8. PYROELECTRIC DETECTOR
9. WATER COOLED SLIT

* ESTABLISHMENT OF NEW DATA ANALYSIS SCHEME FOR INTERFEROGRAMS

Fig.3 New Data Analysis Scheme

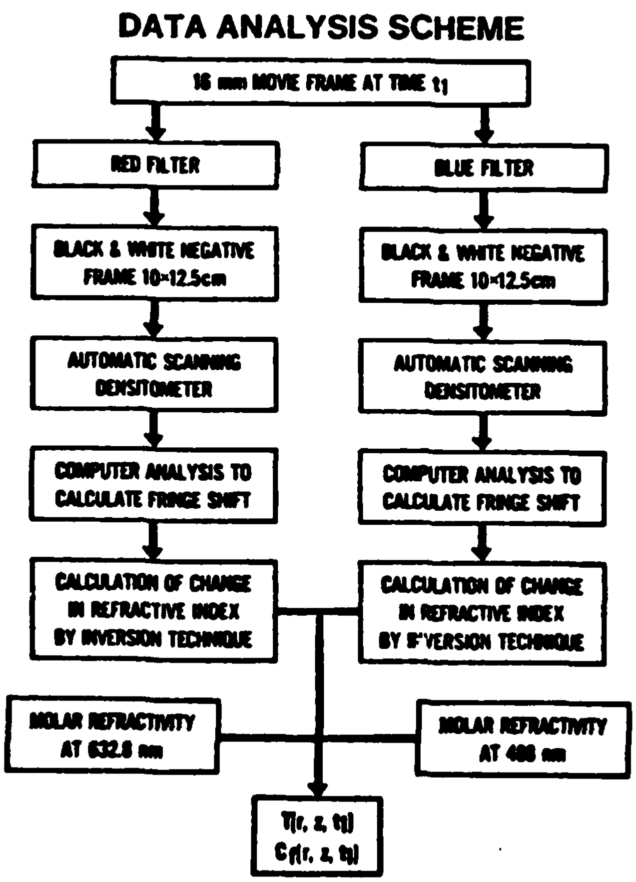
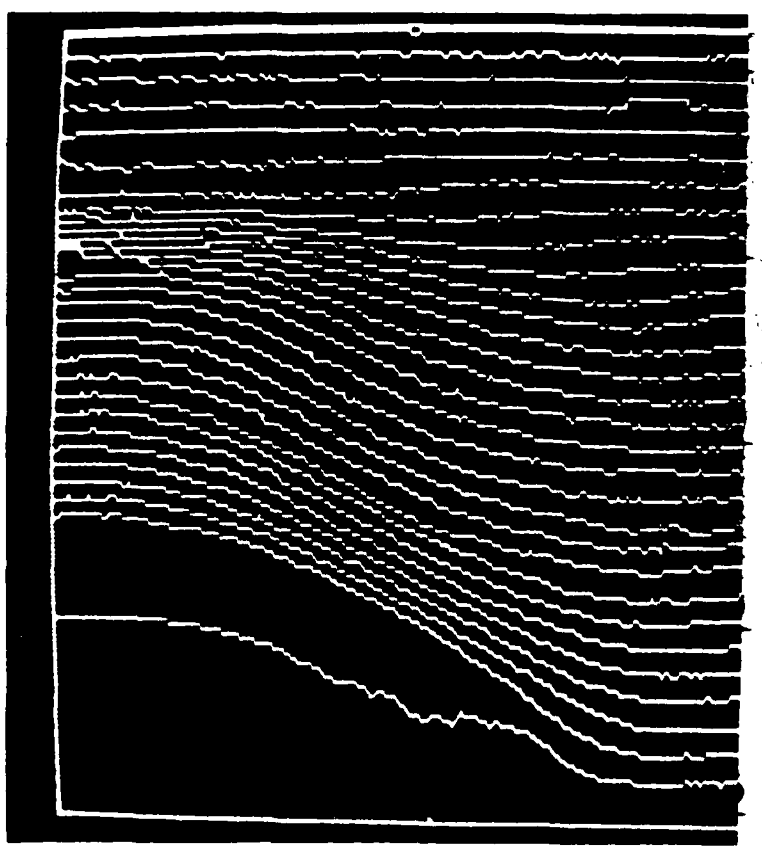


Fig.4 Computer Calculated Contour of Peaks of Fringes



Study of the Fundamental Mechanisms of Unconfined Detonations

John H.S. Lee, Romas Knystautas and
Christiane Guirao

McGill University
Mechanical Engineering Department
Montreal, Canada

That a given combustible mixture can entertain two modes of combustion with abrupt transition from one mode (deflagration) to the other (detonation) under appropriate initial and boundary conditions is a direct consequence of instability. Combustion instabilities encompass a wide spectrum of problems (e.g., pressure oscillations in combustors and engines, flame stabilization (blow-off and flashback), acoustic instability, cellular flames and detonations, turbulent flames). However, the basic underlying mechanism is essentially the same, namely, the non-linear coupling between the burning rate and the gasdynamic flow structure generated by the energy release of the combustion processes themselves. Our early AFOSR sponsored research in the late 60's was mostly devoted to the study of the unstable coupling between the transient gasdynamic flow structure of blast waves and the chemical kinetics in relation to the direct initiation problem. In recent years, our efforts have been devoted to elucidate the mechanisms responsible for the cellular structure of the detonation mode and the role of this instability mechanism on propagation limits. In connection with the investigation of the chemical initiation concept for FAE III beginning in the late seventies, emphasis has been placed on the study of intercoupling between intense turbulence and combustion. The regime of interest is near the limits where the positive effect of higher turbulent diffusivities in increasing the burning rate begins to be offset by the negative quenching effect from too rapid a mixing with cold unburnt gases in the reaction zone. In this presentation we shall first describe the results of our investigation on the cellular structure of fuel-air detonations and its application to predict the dynamic properties of fuel-air explosives (i.e., initiation energies and limits). Substantial efforts have also been devoted to the study of turbulent flame accelerations and high-speed turbulent deflagrations in the current AFOSR program. The results of this aspect of the work will also be presented.

Following the success in formulating the linkage between detonation cell sizes and the dynamic detonation properties (i.e., critical tube diameter, initiation energy and limits), the present year research efforts have been mostly centered on systematic experimental measurements of cell sizes in various fuel-air mixtures. The reason for this is two-fold: first, to test the validity of the fundamental relationship between the detonation cell size λ and the critical tube diameter d_c (i.e., $d_c \simeq 13\ \lambda$ for round tubes and $d_c \simeq 10\ \lambda$ for rectangular channels) over a wide range of fuels and second, to accumulate cell size data in order to use this fundamental quantity to characterize the detonation sensitivity (or the dynamic detonation properties) of various fuels.

The detonation cell data of the H_2-air system measured last year in two detonation tubes (5 cm in diameter x 4 m long and 15 cm in diameter x 6.15 m long) over the composition range from 16% H_2 to 60% H_2 were extended this year to limit compositions from 16% to 13.8% H_2 using a larger detonation tube (30 cm in diameter x 17.25 m long). The detonation cell diameter of H_2-air mixtures (measured from 2 m aluminum foil strips using the smoked foil technique and also estimated from the oscillations of pressure records) are compared in Fig. 1 with the cell sizes of C_2H_4, C_2H_6 and C_3H_8-air mixtures measured in both 15 cm and 30 cm detonation tubes. Both C_2H_6 and C_3H_8 have almost the same detonation cell diameters for equivalence ratios ranging from ϕ = 0.785 to ϕ = 1.25, hence the same sensitivity to detonation. Based on cell diameters, the sensitivity to detonation of stoichiometric hydrogen-air mixtures is approximately 1.7, 3.6 and 3.5 times greater than the sensitivity of stoichiometric ethylene-air, ethane-air and propane-air mixtures, respectively.

In collaboration with Sandia National Laboratories Albuquerque, CMI (Christian Michelsen Institute) and FBT (Defense Construction Services) in Norway and DRES (Defense Rsearch Establishment Suffield, Canada) field tests to measure the critical tube diameters of H_2-air and C_2H_4-air mixtures for the successful transformation of a planar (confined) detonation into a spherical (unconfined) detonation were carried out. For the H_2-air experiments three detonation tubes (76 cm, 91 cm and 121 cm in diameter, 3.05 m, 4.06 m and 3.05 m long) attached to a 6 m long plastic tube were used. For the C_2H_4-air mixtures, the experiments were performed in three detonation tubes (43.5 cm, 95.4 cm and 136.5 cm in diameter, 5.06 m, 5.45 m and 5.53 m long) attached to a plastic bag. These large-scale experiments indicate the validity of the empirical correlation $d_c = 13\ \lambda$ and support the use of cell size data to estimate critical tube diameters of reactive mixtures. Analyses to correlate cell size data with shock tube induction kinetics and other dynamic properties (e.g., critical energies and composition limits) have also been performed and the results will be presented.

In an effort to elucidate on the fundamental significance of the empirical correlation $d_c = 13\ \lambda$, an experimental program has been carried out to establish the influence of geometry on the transmission from planar to unconfined detonations. Rectangular orifices of various L/W ratios as well as elliptical and triangular orifice plates have been investigated. For triangular, elliptical and square orifices, the $d_c = 13\ \lambda$ correlation is still valid based on the mean value of the inscribed and circumscribed circles. However, for rectangular orifices of large L/W ratios, the W/λ ratio decreases rapidly and reaches asymptotically a limiting value of about 3 as L/W increases. Thus it appears that the two-dimensional geometry differs significantly from the three-dimensional one and the reason for this is still unknown. Intense efforts are currently devoted to clarify this puzzling result which may hold the key to the correct explanation of the mechanisms responsible for the universality of the $d_c = 13\ \lambda$ correlation for the circular geometry.

In connection with chemical initiation studies under the FAE III concept, considerable efforts have been devoted to intense turbulent combustion. It has been previously established that the central problem is the problem of rapid turbulent mixing and chemical reactions under very high turbulence levels. The main studies carried out this year have been concerned with i) the turbulent jet ignition and quenching problem and ii) the limiting attainable turbulent flame speed. The study of the turbulent jet ignition and quenching problems centers around the critical conditions when competing effects between turbulent mixing rates and kinetic rates balance each other. Very intense turbulence levels can be created in jets and scales and intensities can also be readily controlled via screens placed at the jet exit plane. The stationarity of the mixing and reaction zones can also permit detailed diagnostics to be carried out. The present experiments investigate the quenching of flames propagating from one chamber into another one through an orifice. Depending on the pressure developed by the flame in the upstream (ignition) chamber, the quenching phenomenon may be divided into three regimes: i) for very low flame speeds, a "Peclet" regime in which the quenching process is controlled by the loss of heat and free radicals to the orifice wall, ii) a "turbulent mixing" regime in which turbulent mixing downstream of the orifice plays an important role and iii) a "gasdynamic" regime where the changes in temperature associated with the underexpanded jet structure also contributes to the overall quenching process. The present experiments concentrate on the third regime. In small-scale laboratory experiments and large-scale field tests conducted at McGill University and Raufoss, Norway, respectively, hot combustion products generated in an ignition tube were ejected as supersonic jets through circular orifices into a combustion chamber. Successful flame transmission was determined from combustion chamber pressure records. The critical conditions for quenching were obtained by varying the orifice diameter or by accelerating the flame through obstacle grids placed in the ignition tube. The quenching diameters measured in the present experiments characterize constant volume explosion quenching since large pressures were developed in the ignition tube prior to flame transmission through the orifice as the result of the large ignition tube diameter to orifice diameter ratios and the large distance between the ignition source and the orifice. The quenching diameters of hydrogen, acetylene, ethylene and methane-air mixtures plotted in Fig. 2 with respect to the equivalence ratio are more than one order of magnitude larger than the corresponding maximum experimental safety gap (MESG) values which occur at lower ignition tube pressures. In general, the results indicate that the ratio of the quenching diameter for constant volume combustion to the MESG diameter increases as the mixture becomes less sensitive. Additional experiments on the dependence of the quenching diameter on the ignition tube pressure indicates that as the ignition tube pressure increases, the quenching diameter initially increases rapidly, reaches a maximum and gradually decreases. The present results led to the formulation of a turbulent quenching criterion based on the equality of the characteristic gasdynamic mixing time and the characteristic combustion time. Such a criterion is similar to the criterion for the blow-off limit of stabilized flames and future extension of this work will contribute towards the problem of flame holder design in high-speed flows.

The study of ultimate turbulent flame speeds intends to answer the fundamental question "what is the maximum burning rate in a turbulent flow?" Experiments were carried out in long circular tubes (8 m and 11 m in length) of various diameters D (5 cm and 15 cm in diameter). Spiral coils or repeated circular orifice plates (diameter d) of different blockage ratios BR = $1 - (d/D)^2$ were inserted into the tube as turbulence generators. Flame speeds (relative to laboratory coordinates) and pressure-time histories were measured in H_2, C_3H_8 and CH_4-air mixtures over a wide range of mixture concentrations. Typical results for the flame speed variation with distance from the ignition source in H_2-air mixtures are shown in Fig. 3. A 3 m length of spiral coil (BR = 0.44) was used to generate turbulence. For all H_2 concentrations, rapid acceleration to steady-state conditions within the obstacle region was observed. The ultimate turbulent flame speeds range from about 100 m/s at 10% H_2 to quasi-detonation velocities of the order of 1700 m/s in the fuel range from 25% to 45% H_2 with transition to detonation at about 17% H_2. Therefore, in general, the present results indicate the existence of a continuence of turbulent flame speeds up to detonation levels as the mixture composition approaches the stoichiometric one from both lean and rich limits. However, critical values of mixture compositions exist at which sudden transition to the detonation mode occurs. These results demonstrate the dominant role played by boundary conditions (hence the gasdynamic flow structure) on the combustion process of very high-speed deflagrations. Ultimate flame speeds achieved with a 3 m spiral in H_2, C_3H_8 and CH_4-air mixtures are plotted in Fig. 4 with respect to the equivalence ratio. The results indicate that turbulent flame acceleration to an ultimate flame speed may be divided into three regimes. In the "quenching" regime, the ultimate flame speed results from the balance between augmentation and quenching processes due to flame stretching and rapid cooling as a result of turbulence. In the "gasdynamic" regime when the flame propagates into a high temperature and high pressure region resulting from the leading shock, quenching due to turbulent mixing is less efficient. If transition to detonation is not possible due to the constraints imposed by the environment, gasdynamic choking of the gas ahead of the leading shock becomes important in limiting the ultimate flame speed. In the "detonation" regime, the flame transits to "quasi-detonation" and propagates at a speed slightly lower than the normal Chapman-Jouguet detonation velocity due to severe pressure losses across obstacles. For H_2-air mixtures, these three regimes are quite distinct in Fig. 4. The boundary for the first two regimes is around 13% H_2 ($\phi = 0.356$) and the boundary for the "detonation" regime is around 25% H_2 ($\phi = 0.793$). For up to 45% H_2 ($\phi = 1.95$), the ultimate flame speed stays in the same regime. However, these concentration boundaries are expected to shift for different apparatus geometry and obstacle configuration. For C_3H_8-air mixtures, the boundaries for the three regimes are not well defined. The ultimate flame speed increases gradually from around 100 m/s at 2.7% C_3H_8 ($\phi = 0.66$) to around 1600 m/s at 5.5% C_3H_8 ($\phi = 1.385$). The peaking of the ultimate flame speed at 5.5% C_3H_8 which is also observed for the C-J detonation velocity of C_3H_8-air mixtures indicates that the flame propagation mechanism is dominated by chemical kinetics. CH_4-air mixtures are the less sensitive system. Except around the stoichiometric composition (9.5% CH_4), the ultimate flame speed is less than 250 m/s and decreases progressively as the mixture composition deviates from the stoichiometric one. This indicates that the ultimate flame speed corresponds to the "quenching" regime. Additional experiments using other obstacle configurations and scales of apparatus are definitely needed to provide a better understanding of the various limiting mechanisms. The practical aspects of this study will contribute towards the design of turbulent combustors in advanced propulsion systems.

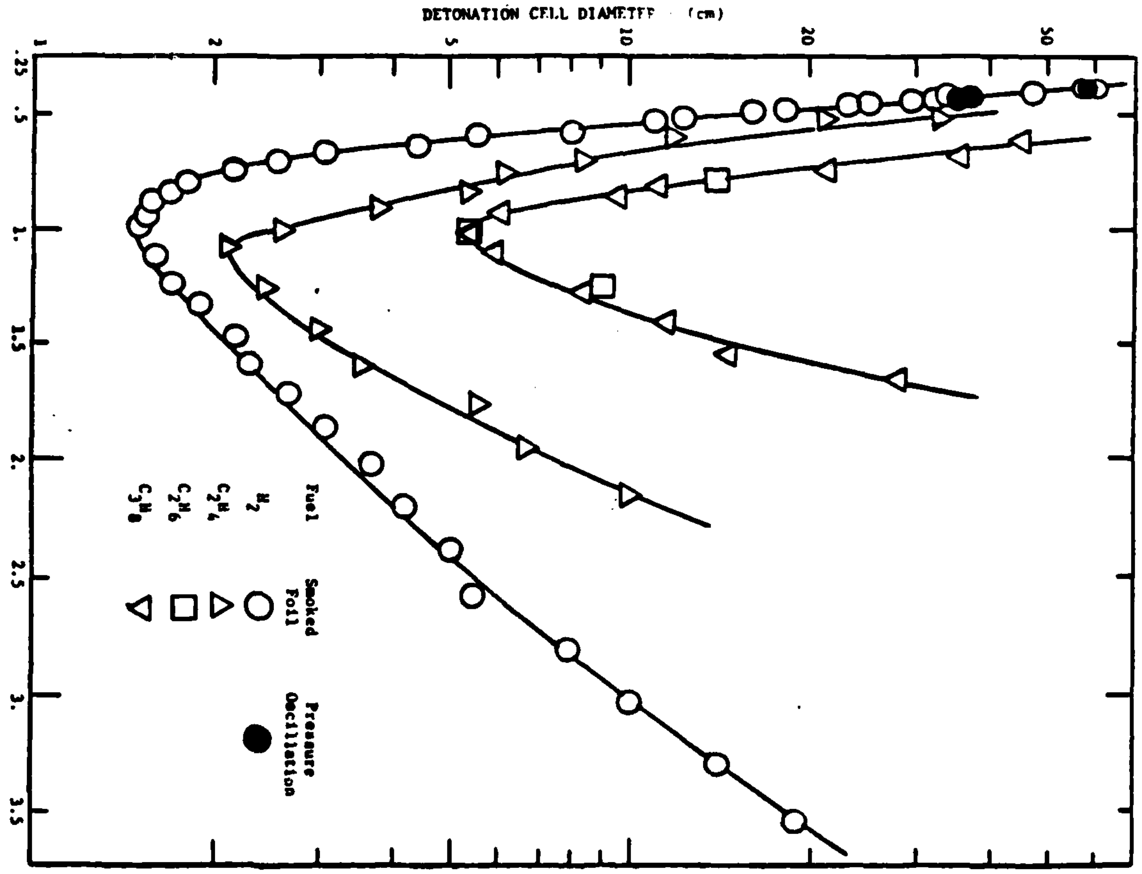

DETONATION CELL DIAMETER (cm)
EQUIVALENCE RATIO
Fuel
H_2
C_2H_4
C_2H_6
C_3H_8
Smoked Foil
Pressure Oscillation

FIG. 1.

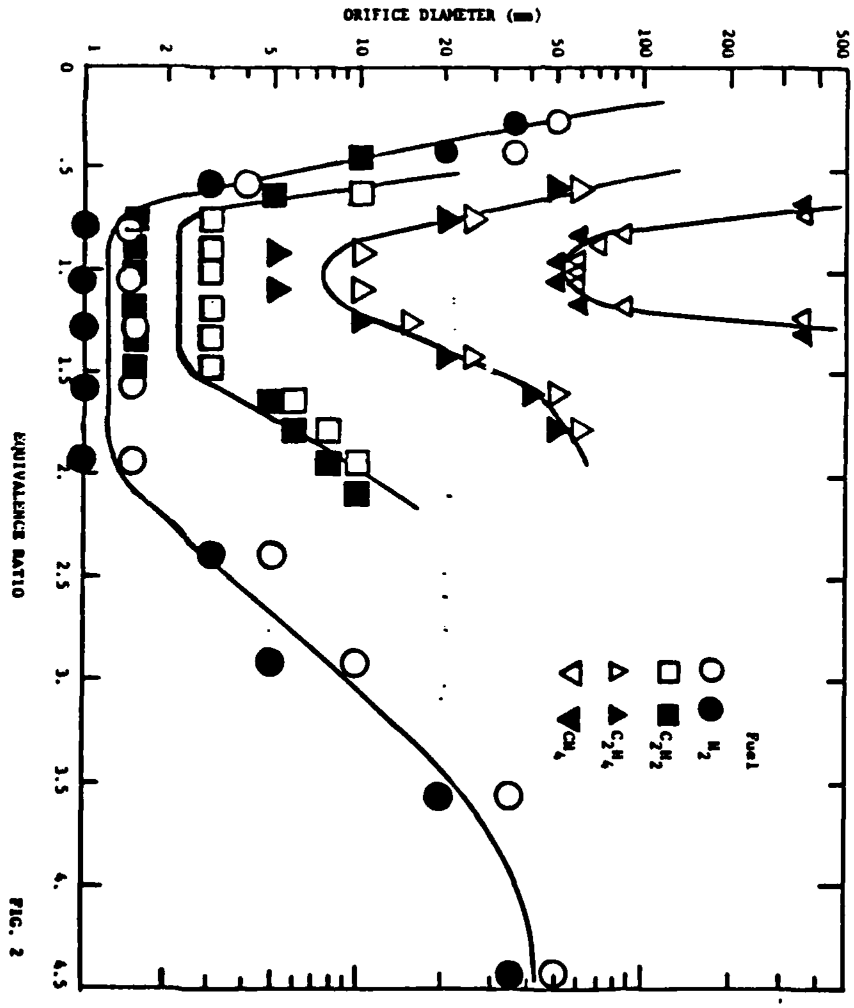

ORIFICE DIAMETER (mm)
EQUIVALENCE RATIO
Fuel
H_2
C_2H_2
C_2H_4
CH_4

FIG. 2

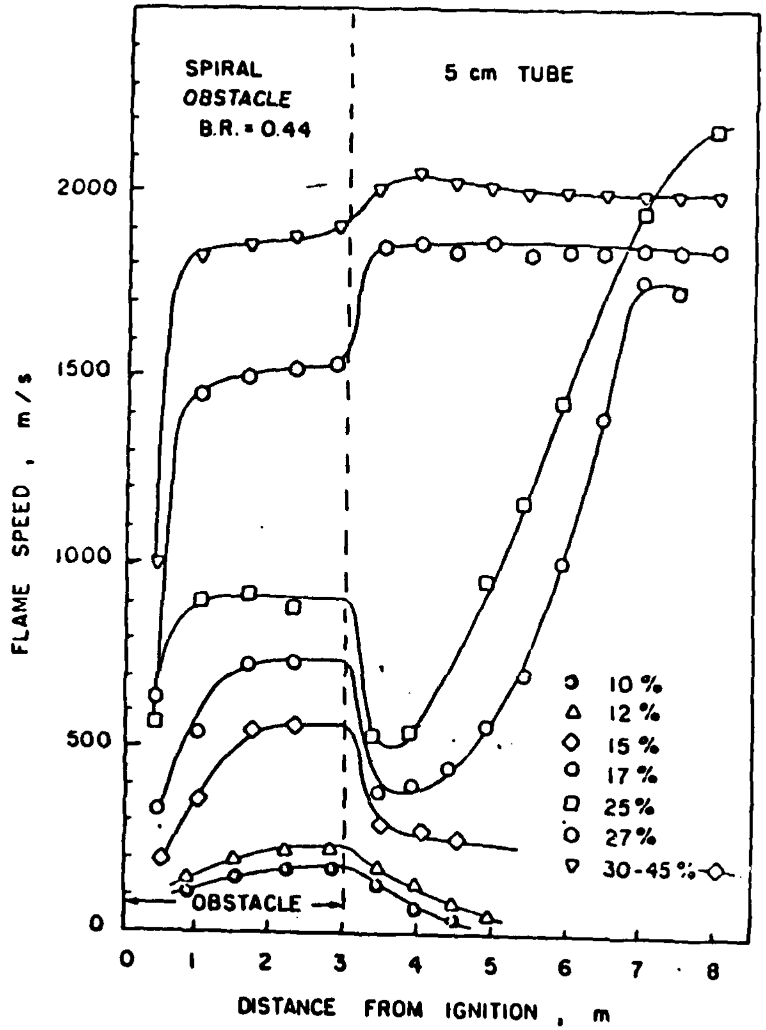

SPIRAL OBSTACLE B.R. = 0.44
5 cm TUBE
FLAME SPEED, m/s
DISTANCE FROM IGNITION, m
OBSTACLE
10 %
12 %
15 %
17 %
25%
27%
30-45 %

FIG. 3

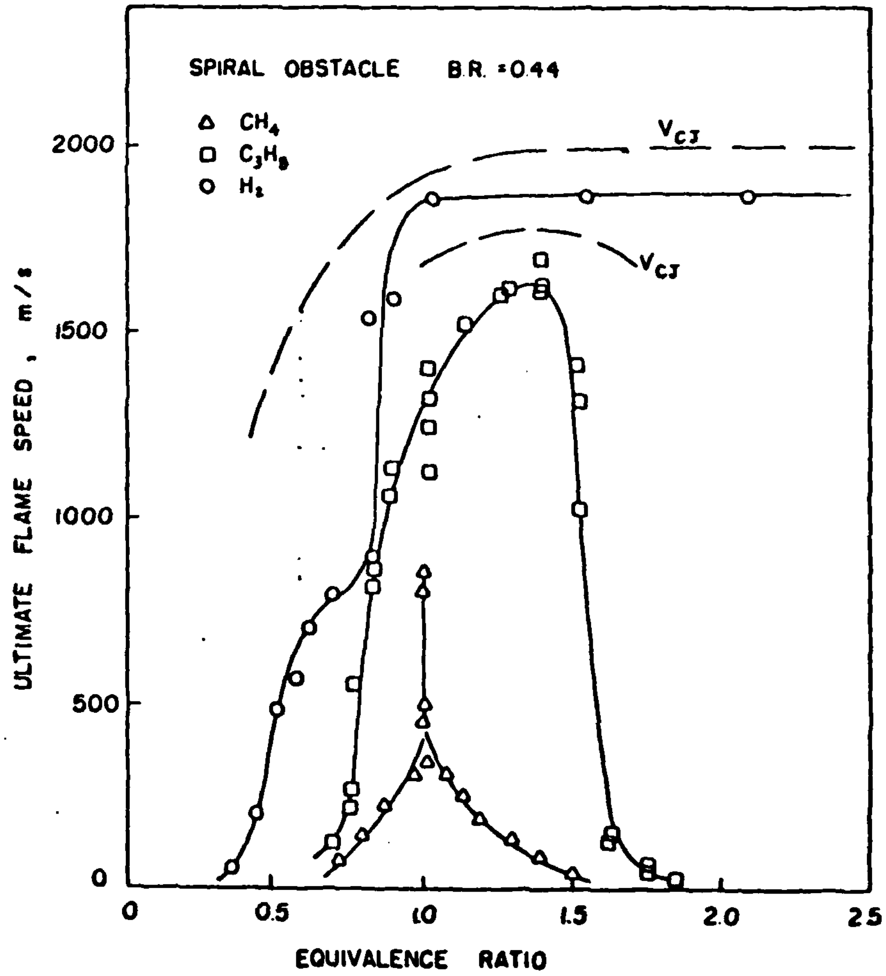

SPIRAL OBSTACLE B.R. = 0.44
CH_4
C_3H_8
H_2
V_{CJ}
V_{CJ}
ULTIMATE FLAME SPEED, m/s
EQUIVALENCE RATIO

FIG. 4

IGNITION, ACCELERATION, STABILITY AND LIMITS OF DETONATION

H. Wagner & W. Jost
University of Wales - England

ABSTRACT NOT AVAILABLE

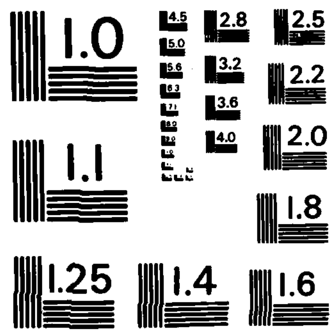
AD-A121 647 ABSTRACTS: 1982 AFOSR CONTRACTORS MEETING ON AIR BRETTHING COMBUSTION DYN..(U) UNIVERSITY OF SOUTHERN CALIFORNIA LOS ANGELES DEPT OF MECHANI.. 3/3

UNCLASSIFIED M GERSTEIN ET AL. NOV 82 AFOSR-TR-82-0841 F/G 21/1 NL

END

FILMED

DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

DETONATION CHARACTERISTICS OF SOME DUSTS AND LIQUID-DUST SUSPENSIONS (AFOSR-79-0093)

J. Arthur Nicholls, C. William Kauffman, Martin Sichel

Gas Dynamics Laboratories, Department of Aerospace Engineering
The University of Michigan, Ann Arbor, MI 48109

The main objective of this research is to determine the detonation characteristics of high explosive dusts when dispersed in air under unconfined conditions. A variation of this problem which is of interest is that wherein the dust is entrained in liquid fuel droplets. This aspect could be referred to as three phase detonation. Important factors which bear on these problems and which are being investigated include the properties of the dust, the concentration, the particle size, the effects of excess oxygen, the energy of the initiating source, and the structure of the reaction zone. For a range of conditions, then, it is desired to determine the pressure history within and behind the reaction zone, the wave velocity, the ignition time delay of the particles behind the leading shock wave, the energy required for initiation of detonation, and, in addition, to obtain high speed framing and streak photographs of the wave and reaction zone. In order to obtain this data, to more adequately assess it, and to gain predictive information, a combined experimental-theoretical approach has been pursued.

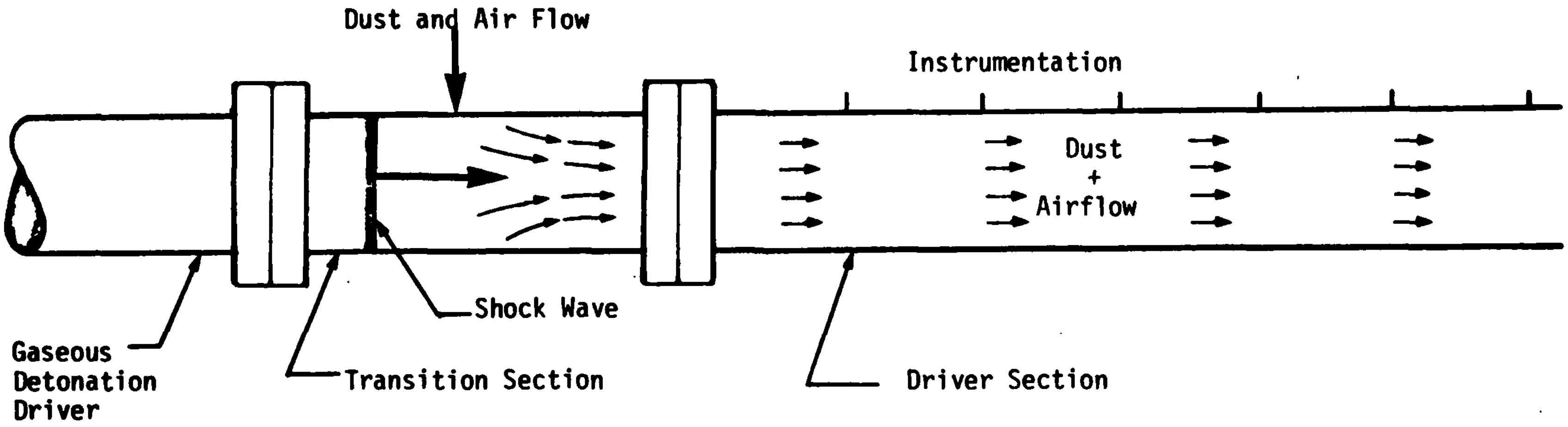
On the experimental side, a unique modification of the shock tube technique has been employed. A schematic of the setup used for the detonation studies is shown in Fig. 1(a). A circular cross section driver is separated from the rectangular driven section by a transition section. A small gas flow (air or oxygen) introduces the dust into the transition section and the main airflow, also introduced into the transition section, blows the mixture through the driven section. The velocity in this section, about 20 ft/sec, is sufficient to keep the particles airborne and thus to simulate a one-dimensional cloud. A strong shock wave, generated by the detonation of $2H_2 + O_2 + 1.5$ He in the driver, ignites the dust-air mixture. The subsequent wave propagation is monitored so as to determine whether detonation is achieved. Measurements made include pressure, wave arrival times (velocity), and light emission. High speed photographs are also obtained. Figure 2(b) shows the configuration, schematically, for determining the ignition time delay and characteristics for a single liquid fuel droplet (decane) with entrained RDX particles. The single droplet is supported on a needle. For these studies, high pressure helium serves as the driver to transmit a shock into the air or oxygen in the driven section. The shock wave-droplet interaction is recorded by streak photography.

Our earlier experiments utilized very small particles, RDX/E, and larger particles, RDX/A, dispersed in air. It was only with the large particles and with some oxygen enrichment that detonation was achieved. Following up on this, experiments were conducted in air wherein various amounts of the oxidizer dust, ammonium perchlorate (AP), were mixed in with the RDX dust. Again, detonation was realized only with the large particles. This size effect is significant and is believed to arise from the inertia of the large particles. That is, the large particles take much longer to accelerate to gas velocity behind the shock and hence the heat transfer rate to the particles is much higher. In those RDX-AP experiments where detonation occurred, the pressure ratios measured were greater than in the case of RDX/A-O_2 enriched air detonations. This result was in agreement with theoretical calculations. Experimental results showing the variation of wave propagation Mach number along the tube are shown in Fig. 2. The percentages for the dusts express the amount, by mass, in dust form. The equivalence ratio is denoted by ϕ and the driver pressure represents that before the driver gas is detonated. As indicated, only 1/4 of the driver volume is filled with the combustible gas. The data show that the two leaner mixtures are detonating but that the richest one is not. This conclusion is based on pressure records as well as these velocity records.

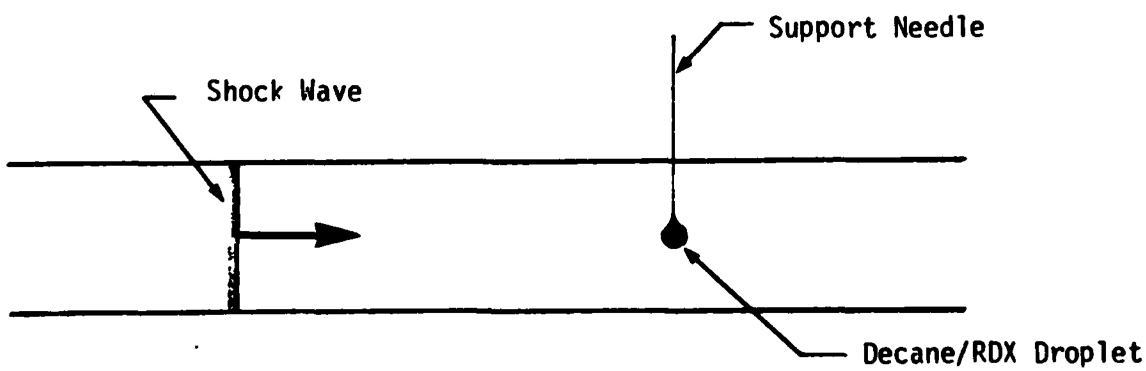
Figure 3 is a streak photograph of the interaction of a Mach 3.5 shock with a 3000 μm decane-RDX/E drop in an oxygen atmosphere. A small amount of Cabosil (Al_2O_3) was mixed in with the RDX so as to reduce the tendency of the particles to stick together. It can be seen that there is an explosive ignition in the wake of the drop after an ignition delay time of about 85 μsecs. Comparison of this case with that for a decane drop with no dust reveals that the dust case yields appreciably shorter ignition delay times. This is quite significant in that the detonability is very dependent on the ignition delay time. These studies are continuing and various shock strengths (temperatures) and liquid to dust ratios will be tested in oxygen and air atmospheres.

In view of the importance of ignition time delay to detonability, whether it be gaseous, liquid spray, or dusts, the analytical efforts are concentrating on the relaxation zone behind the shock wave. The equations for the two phase flow, which incorporate empirical expressions for the Nusselt number and drag coefficient, have been programmed to calculate the conditions throughout the induction zone of dust detonations. The increase in pressure and temperature due to the presence of the dust, even if non-reactive, is predicted. The heating and reaction of individual particles is now being introduced into the model. For the particles, internal temperature variation as well as surface and internal heterogeneous reactions are being considered. Some preliminary results are available.

Fig. 1. MAIN FEATURES OF THE APPROACH



a) Detonation Characteristics of *High Explosive Dust.*
(Pressure, wave velocity, light emission, photography)



b) Ignition Process in Three Phase Detonation

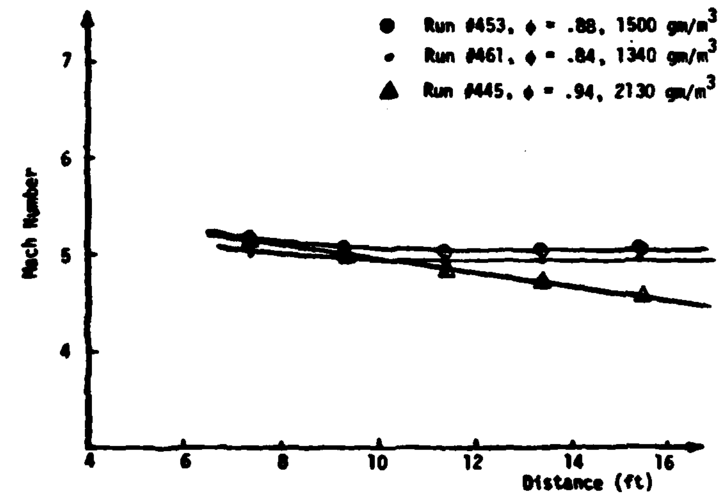


Figure 2. Wave Mach Number, 83% RDXA + 17% Ammonium Perchlorate 100% Air, Driver Pressure 119.3 psia, 1/4 Driver.

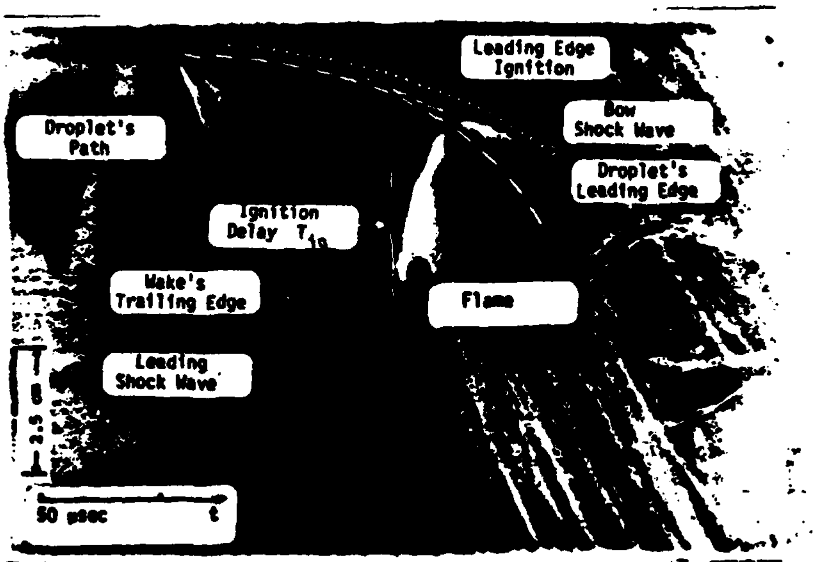


Figure 3. Run #502, RDX-E/Decane/Cabosil Droplet, 3000 μm, M = 3.5.

EFFECT OF HEAT AND MASS ADDITION ON AN ESTABLISHED SUBSONIC FLOW OF AIR

R. Edse and T. Sheaf

Department of Aeronautical and Astronautical Engineering

The Ohio State University

This study is to provide information on the effect of fuel flow changes in turbojet engines on the performance of the compressor.

When pressure waves generated in the combustion chamber of a turbojet engine by fuel addition travel upstream to the compressor, operating at optimum condition, the performance of the compressor may decrease sufficiently to cause transient air flow reductions of considerable magnitude. Since the flow is subsonic, such pressure disturbances are propagated rapidly through all compressor stages and may cause stalled flow in some stages. To obtain an insight into the magnitude of this effect the pressure changes produced by heat and/or mass addition to a steady subsonic flow were calculated for both the region upstream and that downstream of the section where the disturbance was created.

First only the effect of heat addition to a steady subsonic flow of air passing through a simple duct was studied. To obtain explicit solutions it was assumed that under the conditions of interest air can be considered to behave like a calorically perfect gas and that the flow through the straight channel is inviscid. The effect of heat addition to such a flow was calculated by means of the fundamental equations governing this flow. The equations, shown in Fig. 1a, are for the case that the initial pressure at the channel exit is held constant as heat is added to the flow ($p_2 = p_1$). For a given initial Mach number of the undisturbed flow (M_1) the upstream (M_1) and downstream (M_2) Mach number produced by a certain heat release factor q/c_pT_1 can be calculated readily. Then, with these results, the corresponding temperatures, pressures, and flow speeds were calculated. The effect of the amount of heat added to the flow on the mass flow rate is shown in Fig. 2a for different initial flow Mach numbers.

The analysis of the effect of heat and mass addition by means of an actual combustion process is quite involved and cannot be solved explicitly. Therefore, iterative calculations were made for a number of specified conditions. The solutions are based on the case that the downstream flow is already choked before any fuel flow changes are made. This assumption is actually quite realistic since the flow through the turbine of many turbojet engines is choked. A flow diagram of the iterative calculation is shown in Fig. 1b and the results are shown in Fig. 2b. In these calculations gaseous hydrogen was used as the fuel because of its high combustion enthalpy per unit mass. The hydrogen flow entered the subsonic airflow at sonic speed so that the mass flow rate of hydrogen could be expressed in terms of its stagnation pressure, $P^{o}_{H_2}$.

According to this analysis significant changes of the airflow through a turbojet engine can be produced by rather modest fuel flow changes. An apparatus is being designed and will be constructed shortly to determine whether the rates of the predicted changes exceed those which can be handled by the accelerations and decelerations possible with the fuel flow controls of present production engines operated at optimum conditions.

$$M_1\sqrt{1+\frac{\gamma-1}{2}M_1^2}\left(\frac{1+\frac{\gamma-1}{2}M_1^2}{1+\frac{\gamma-1}{2}M_1^2}\right)^{\frac{\gamma}{\gamma-1}} = \frac{M_2\sqrt{1+\frac{\gamma-1}{2}M_2^2}}{\sqrt{1+\frac{q}{C_pT_1^{\circ}}}} \quad \text{---(1)}$$

$$M_2 = \sqrt{\frac{1}{\gamma}\left\{(1+M_1^2)\left(\frac{1+\frac{\gamma-1}{2}M_1^2}{1+\frac{\gamma-1}{2}M_1^2}\right)^{\frac{\gamma}{\gamma-1}} -1\right\}} \quad \text{---(2)}$$

$\frac{q}{C_pT_1}$ - heat release factor

M_1 - before thermal wave

M_2 - after thermal wave

M_1 - initial flow

Fig. 1a

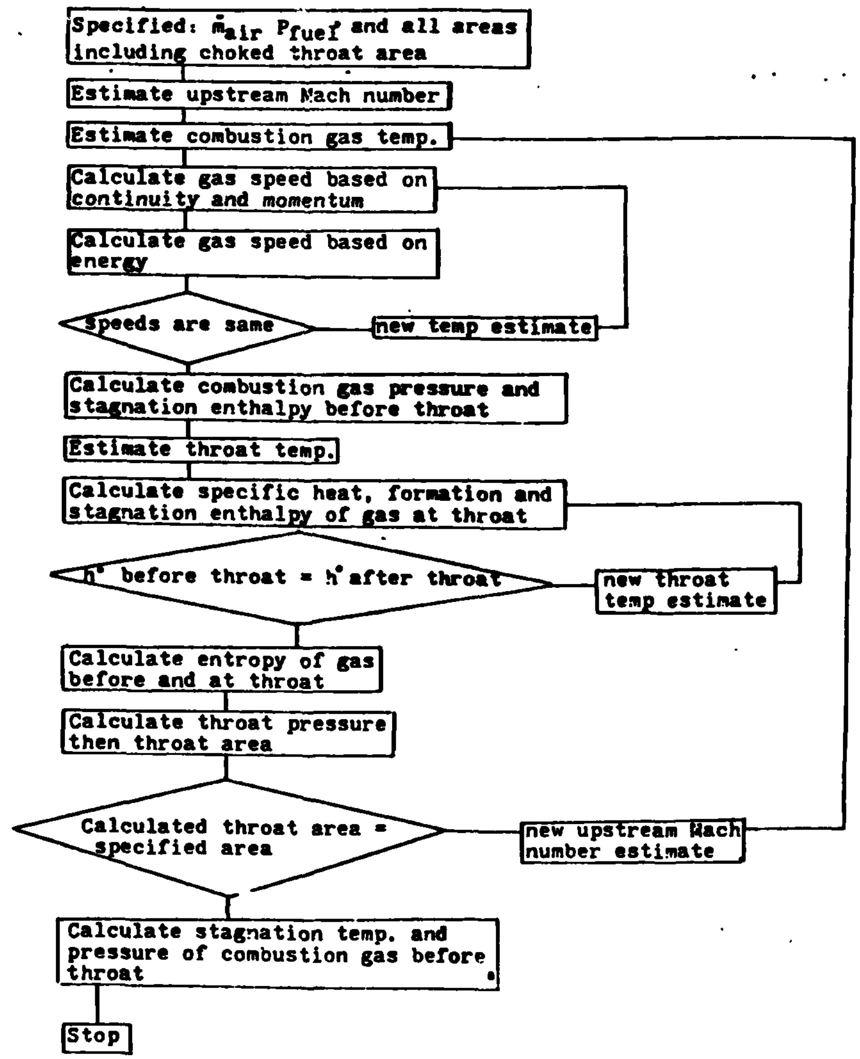


Fig. 1b

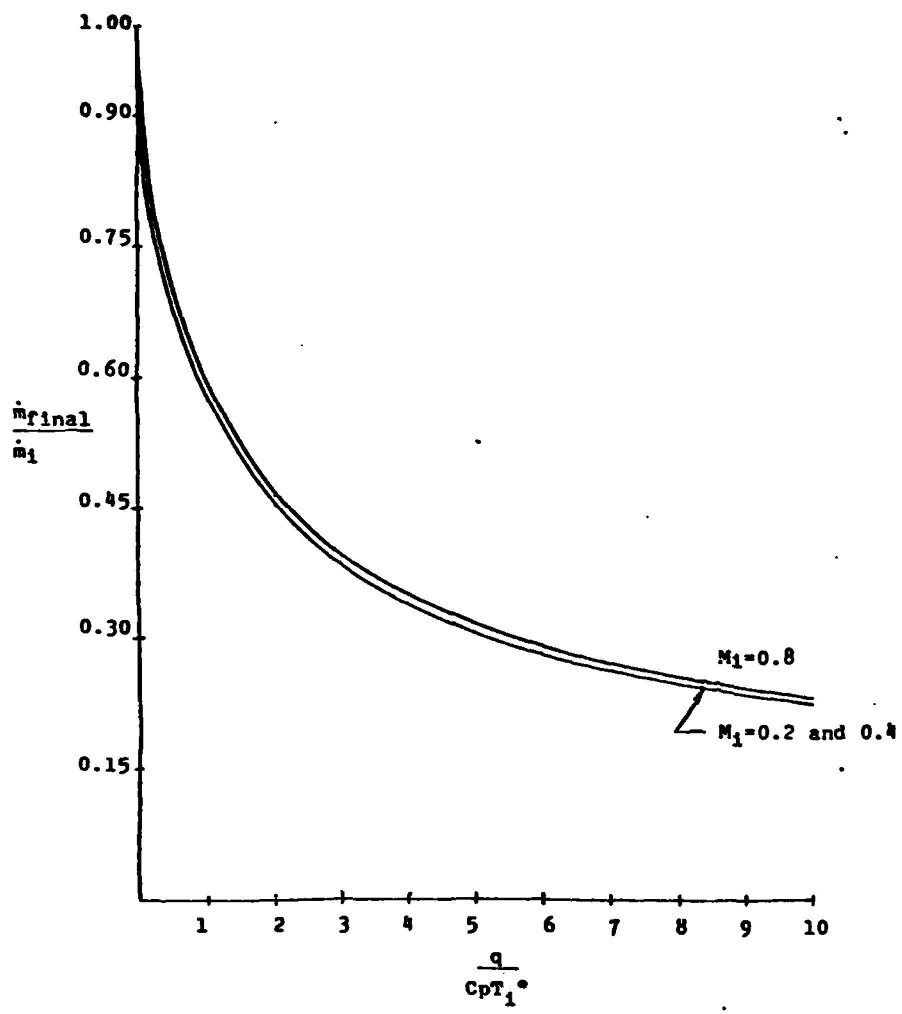


Fig 2a. - Mass flow rate vs. heat addition

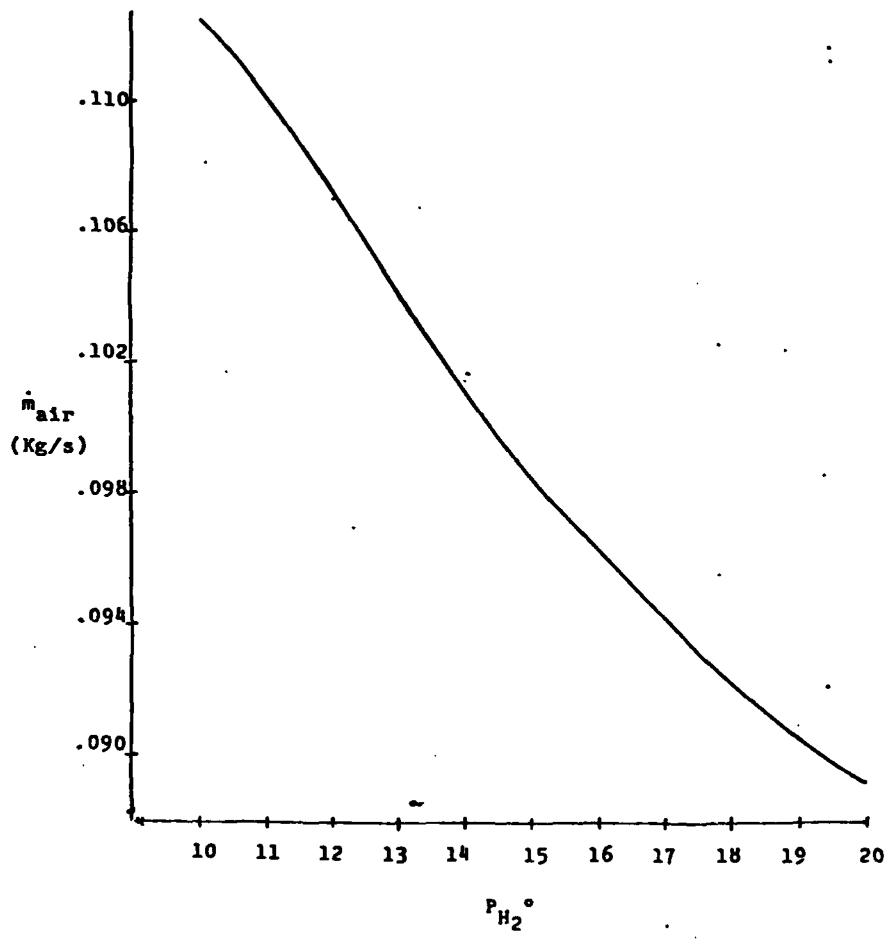


Fig 2b.- Primary mass flow ($\dot{m}_{air}$) vs. $P_{H_2}°$